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SATELLITE LOCAL AREA NETWORK INTER-SATELLITE LINK

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Final Report

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14. ABSTRACT

Report developed under SBIR contract for topic AF99-074. The purpose of this effort was to explore concepts and technologies for a lightweight, low power, high data rate, secure and standards based satellite local area network inter-satellite link (ISLs) communication system. Operational and design constraint requirements, hardware and software were analyzed, defined and documented in an operations concept and a requirements document. A candidate CDMA ISL system design was specified using existing and in development wireless communication system hardware and software components. The defined ISL system was specified as capable of delivering 100 Mbps data transfer rates between satellites, 3 mm satellite relative position determination and 20 ps satellite cluster timing synchronization. The design was specified to achieve 20 W, 5 kg, 0.3 m^3 and $300K (in quantities of 300) power, weight, volume and cost constraints. Potential applications of the effort are ISLs, terrestrial high speed CDMA wireless communication links and all manner of secure, 100 Mbps wireless data tranmission.

15. SUBJECT TERMS

Satellite LAN, Inter-Satellite Link, ISL, CDMA, SBIR Report, ranging, timing, mbps payload data links

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LIST OF ABBREVIATIONS/ACRONYMS

—A—

ACK/NAK - Acknowledgment/Negative Acknowledgment
A/D - Analog-To-Digital
ADC - A/D Converter
AFRL/VS - Air Force Research Laboratory Space Vehicles Directorate
ANSI - American National Standards Institute
API - Application Program Interface
ARPA - Advanced Research Projects Agency
ARQ -Automatic Repeat Request
ASIC - Application Specific Integrated Circuit
ATM - Asynchronous Transfer Mode

—B—

BERs - Bit Error Rates

—C—

C^2 - Command and control
CASE - Computer Aided System Engineering
C&DH - Communications And Data Handling
CCSDS - Consultative Committee on Space Data Systems
CDMA - Code Division Multiple Access
CHI - Computer-Human Interface
CMOS - Complementary Metal Oxide Semiconductor
COTS - Commercial-Off-The-Shelf
CRC - Cyclic Redundancy Code

—D—

D/A - Digital-To-Analog
DES - Data Encryption Standard
dBW - Decibels Relative To 1 Watt
DLC - Data Link Control
DLP - Data Link Protocol
DS-CDMA - Direct Sequence CDMA
DSL - Digital Subscriber Loop
DSSS - Direct Sequence Spread Spectrum (DS-CDMA)

—E—

E_b/N_o - Signal Energy Per Bit/ Noise Energy Per Hertz
EDU - Engineering Development Unit
ESG - Electronic Signal Generator

—F—

FCS - Frame Checking Sequencing
FCC - Federal Communications Commission
FDDI - Fiber Distributed Data Interface
FDMA - Frequency Division Multiple Access
FEC - Forward Error Correction
FH-SS - Frequency-Hopping Spread Spectrum
FIFO - First-In-First-Out
FPGA - Field Programmable Gate Array
FSP - R&S Frequency Spectrum Processor

—G—

Gb/s - Gigabit Per Second
GEO - Geostationary Earth Orbit
GMTI - Ground Moving Target Indication
GPS - Global Positioning Satellite
GUI - Graphical User Interface

—H—

HDLC - High-Level Data Link Control
ISL-DLP - ISL Data Link Protocol

—I—

I-Frame - Information Transfer Frame
ICs - Integrated Circuits
ID - Identifier
IEEE - Institute of Electrical and Electronics Engineers
IETF - Internet Engineering Task Force
IF - Intermediate Frequency
IP - Internet Protocol
ISA - Instrument Society Of America
ISL - Inter-Satellite Link
ISLP - Inter-Satellite Link Protocol
ISO - International Standards Organization
ISPs - Internet Service Providers

—L—

LAN - Local Area Network
LEO - Low Earth Orbit
LOS - Line Of Sight
LVDS - Low-Voltage Differential Signaling

—M—

MAN - Metropolitan Area Network
MAC - Media Access Control
MMS - Manufacturing Message Specification (ISO-9506)
MTU - Message Transmission Unit

—N—

NASA - National Aeronautics and Space Administration
NDIS - Network Device Interface Specification

—O—

ODI - Open Data-Link Interface
OFDM - Orthogonal Frequency-Division Multiplexing
OSE - Operating System Environment
OSI - Open Systems Interconnection
OSI-RM - OSI Reference Model

—P—

PCI - Peripheral Components Interconnect (bus)

—Q—

QAM-DQPSK - Quadrature Amplitude Modulation Differential Quadrature Phase Shift Keying
QoS - Quality of Service

—R—

R&S - Rhode And Schwartz
RF - Radio Frequency
RFC - Request For Comment
RSVP - Resource Reservation Protocol
RTOS - Real-Time Operating System

—S—

S-Bus - Sun Microsystems Bus
S-Frame - Supervisory Frame
SAR - Sparse Aperture Radar
SBIR - Small Business Innovative Research
SCPS - Space Communications Protocol Standards
SCPS-FP - SCPS File Protocol
SCPS-NP - SCPS Network Protocol
SCPS-SP - SCPS Security Protocol
SCPS-TP - SCPS Transport Protocol
SNMP - Simple Network Management Protocol
SNR - Signal To Noise Ratios
SR- Selective Repeat
SR-ARQ - Selective Repeat ARQ

—T—

TCP - Transfer Control Protocol
TDMA - Time Division Multiple Access
ToS - Type of Service
TS21 - TechSat 21 Program Office

—U—

U-Frame - Unnumbered Command Control Frame
UDP - User Datagram Protocol

—V—

VCA - Virtual Channel Access
VCLC - Virtual Channel Link Control
VLSI - very large scale integration
VME - Versa Module Eurocard (IEEE-1014)
VPNs - Virtual Path Networks

—W—

WAN - Wide Area Network
W-CDMA - Wideband CDMA
WDM - Wave Division Mulitplexing

—X—

XID - HDLC Exchange Information Frame
XTP - Express Transfer Protocol

EXECUTIVE SUMMARY

This Small Business Innovative Research (SBIR) effort defines, identifies and evaluates concepts, architectures, technologies and designs for inter-satellite links (ISLs) used to link collaborating clusters, or swarms, of small satellites flying in close formation working cooperatively via a satellite local area network. The TechSat 21 (TS21) satellite program from the Air Force Research Laboratory Space Vehicles Directorate served as the target ISL application. The TS 21 satellite mission uses up to eight satellites operating as distributed, space based radars linked to form one large, high resolution virtual satellite sparse aperture radar (SAR) for earth surface and earth atmosphere observation missions. A distributed, satellite SAR LAN serves as a most technologically challenging ISL application.

The main performance requirements to be met were: 100 Mbps data transfer rates between satellites, 3 mm satellite relative position determination and 20 ps satellite cluster timing synchronization. Other design constrain requirements included a 20 W, 5 kg, 0.3 m^3 and \$300K (in quantities of 300) power, weight, volume and cost budget. An important SBIR contractual and technically significant requirement included defining an ISL with commercialization potential for non military wireless communication markets.

An operations concept was written to define the needed functionality based on actual applications of ISLs, to provide a requirements basis, to allow evaluation of wireless existing and emerging technologies, and to provide a basis for defining architectures, hardware and software for an operational satellite ISL. The operations concept provided all parties, operators, designers, implementors, testers and integrators with an understandable view of the ISL functions.

An ISL requirements document was written that utilized a template to define requirements by categories and attributes, organized in such a manner as to facilitate different parties views of and needs for ISL requirements. The requirements document provided the necessary single source of specifications for evaluating wireless technologies, defining recommended ISL implementations, performing cost and risk tradeoffs and gaining user community acceptance of ISL implementations. The requirements document also defined the ISL system boundaries.

The physical and data link layer (including media access control) information transmission and reception hardware architecture candidates for satellite LANs and ISLs were identified. Existing and in development satellite system, cellular, personal communications services, and other wireless LAN and transmission/reception hardware provided the base from which hardware candidates were selected.

Upper layer (including network, transport and application) transmission and reception hardware and software (e.g., protocol) candidates for satellite LANs and ISLs were identified and analyzed. A high-level data link control (HDLC) protocol extension mechanism was defined for additional functionality (e.g., encryption, compression) and better performance (e.g., selective repeat automatic repeat request with multiple buffers) while maintaining standard HDLC interoperability.

Previous task outputs were combined and a candidate ISL architecture, hardware and software were defined. ISL requirements were used to evaluate candidates and define the recommended ISL architecture and implementation approach.

An ISL Engineering Development Unit (EDU) was defined from Code Division Multiple Access (CDMA) receiver, transmitter, processing, antenna and interface components. Usage of commercial-off-the-shelf components was identified and maximized for the development of an ISL EDU by 30 Sep 2000.

A radio frequency (RF) based CDMA ISL system was defined that achieves three technology firsts: 100 Mbps wireless CDMA transmission, 3 mm position accuracy determination and 20 ps sender-transmitter timing synchronization, all via only the RF CDMA signal. A commercially marketable 100 Mbps wireless CDMA transmission device is also easily realized from the resulting design.

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1.0 INTRODUCTION

Trends towards less costly approaches to meet space satellite mission requirements have generated new architectures for space systems. One such concept is the idea of collaborating clusters, or swarms, of small satellites flying in close formation working cooperatively to do the job of a larger, more complex satellite, forming a virtual satellite via a space based local area network (LAN). Virtual satellites and virtual satellite missions were proposed by the principal investigator for the National Aeronautics and Space Administration (NASA) satellites and robots nearly a decade ago [S91]. The virtual mission concept is the carrying out of tasks or missions through coordinated use of a number of independent, simple, one function satellites or robots, instead of using one, complex, multi-function satellite or robot. The mission is a virtual mission in that a number of small satellites carry out their individual missions in a coordinated manner, acting as one to perform one higher level, or virtual mission. The small satellites maintain relative autonomy (attitude and control correction) and share processing capabilities. This concept of virtual satellite clusters has four significant advantages for space missions: greatly reduces the cost, reduces the risks, provides for the insertion and utilization of recent technology advancements, and last but not least, allows for the achievement of missions not possible with single satellites. Small satellites can be launched from inexpensive platforms such as airplanes, cruise missiles and small rockets. A multitude of small satellites can be launched from one, large lift vehicle such as the Titan and Delta rockets, and the Space Shuttle, spreading the launch and integration costs over a number of satellites. Risk is reduced in that the failure of a single satellite does not necessarily cause the loss of a mission. Since a number of virtual satellites can be constructed from a given set of small satellites, the loss of one particular function still enables the achievement of many other missions. Risk is also reduced through the ability to utilize small, inexpensive launch vehicles to launch a replacement satellite in much less time than with a heavy lift launch vehicle. Since small satellites are much easier to build, require much less launch vehicle integration effort and time, and can be launched from a number of mobile, existing small and inexpensive launch platforms, newer technology can be incorporated in much less time. Since the time to design, build and launch a small satellite can be reduced by years over that of a large, complex satellite, the technology in the small satellite does not lag its terrestrial counterparts by the almost 10 years found in current satellites. Newer sensor and payload technology, as well as forming a virtual satellite through cooperating satellite clusters, allows for conducting missions not possible with a single, complex, older technology satellite. A single satellite is limited in size, weight and power consumption, while a satellite cluster is unlimited in these areas as well as unlimited in the number of payloads. More satellites with newer technology can be linked to form virtual satellites that can conduct virtual missions not even conceived of at the time the satellites were designed or launched.

The virtual satellite and the corresponding satellite LAN can be constructed by having the payloads or sensors of collaborating clusters, or swarms, of small satellites connected through inter-satellite communication links (ISLs) in order to coordinate the achievement of mission objectives and tasks. The ISLs form the wireless connections of the satellite LAN.

The Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) funded this Small Business Innovative Research (SBIR) effort for the development of an ISL subsystem for the AFRL/VS TechSat 21 (TS21) satellite program. The TS 21 satellite mission uses up to eight satellites operating as distributed, space based radars linked to form one large, high resolution virtual satellite sparse aperture radar (SAR) for earth surface and earth atmosphere observation missions.

The top level objective for the effort became the definition of a TS21 ISL capable of omnidirectional, simultaneous, high data rate, secure communication required to connect up to sixteen satellites at close range ($\leq$ 1 km) and satellite clusters at long range ($>$ 1 km). A number of initial requirements were also placed on the ISL definition including a $\geq$ 100 Mbps data rate, bit error rates, $\leq 10^{-6}$, weight $\leq$ 0.5 kg, power consumption $\leq$ 1 W, and space survivable for 10 years in low Earth orbit (LEO). An additional SBIR contractual requirement was that the resulting ISL be commercially marketable. Near the end of the effort, the 100 Mbps data transmission requirement was replaced by two new requirements: 20 ps satellite cluster timing synchronization and 3 mm satellite relative position determination.

MiTech Incorporated divided the effort into a number of tasks in order to achieve the objectives:

1. Define Operations Concept for Short and Long Range Satellite Cluster LANs
2. Define Satellite LAN Requirements
3. Identify and Define ISL Architecture
4. Identify and Analyze Wireless Software/Hardware Communication Protocols
5. Define ISL Engineering Development Unit (EDU).

Each task provides a part of the required system engineering methodology to achieve the objective of defining concepts, technologies and architectures for an ISL satellite subsystem with the desired capabilities and characteristics. Each task is now discussed in turn.

2.0 SATELLITE LAN ISL OPERATIONS CONCEPT

The operations concept is a description of how the mission statement and mission objectives for a system of interest are accomplished. The system of interest is a set of ISLs used in a satellite LAN or satellite LAN-like applications. This operations concept documents how ISLs, used to link a number of satellites into a single virtual satellite, interact with the various entities involved to achieve the satellite mission objectives. This operations concept provides a means to communicate the purpose, activities, inputs, outputs and physical constraints of ISLs in the context of planned and foreseeable satellite missions. The operations concept provides a common framework for organizations, individuals and systems involved with ISL system application, specification, development and use.

2.1 Purpose

The purpose of this operations concept is to serve as the requirements source for a) defining the needed functionality to implement ISLs for satellite LAN missions, b) evaluating existing and emerging wireless technologies, and c) defining architectures, hardware and software for recommended ISL implementations capable of conducting planned and foreseeable space missions. The operations concept also serves to define the ISL system boundaries. This ISL operations concept provides for a wide range of ISL applications. A wide range and number of satellite missions with satellite LAN-like interconnections should therefore be able to make use of this ISL operations concept for the above stated purposes.

2.2 Scope

The scope of this operations concept is limited to defining ISL operational characteristics arising from the constraints and operations of the various entities involved in achieving satellite mission objectives. Satellite mission, spacecraft subsystem operational details and mission descriptions are restricted to those relevant to ISL operation. Payload and spacecraft operations and command and control (C^2) descriptions are limited to those relevant to ISL operation. Design and launch segment constraint impacts on ISL operations are included.

2.3 Approach

An operations concept is defined through the definition of a technologically stressing ISL operational scenario of an ISL application in an actual, planned satellite mission. This operational scenario was chosen to represent an extremely broad range of ISL operations, covering near term commercial-off-the-shelf (COTS) and new technology challenging ISL implementations. In order to confine the scope of this operations concept to ISL operations and operational characteristics, only ISL related mission operations are described.

A satellite mission overview is presented, followed by a description of ISL related operations and constraints from the following mission entities: 1) spacecraft subsystems, 2) orbital effects, 3) launch vehicle constraints and 4) program design constraints. ISL operations are then presented as a summary of the previous mission entity related ISL operations expanded through additional ISL specific design constraints.

2.4 Operational Scenario - Distributed Sparse Aperture Radar

This operational scenario describes a satellite mission using eight satellites operating as distributed, space based radars linked to form one large, high resolution virtual satellite SAR for earth surface and earth atmosphere observation missions. This scenario is chosen as the worst case ISL operational scenario in that a distributed, satellite SAR LAN is deemed as a most technologically challenging ISL example. This mission poses a number of technological challenges to ISL operational characteristics and ISL implementation.

2.4.1 Mission Overview

A distributed, satellite based SAR mission is envisioned with clusters of eight satellites flying in formation at ranges of a few meters to 5000 km. Each satellite is identical to every other satellite in

the cluster. Each satellite receives radar payload sensor data and must share some or all of that data with all the other satellites. In the worst case, each satellite must receive every other satellite's entire radar payload return sensor data. The entire cluster of satellites is moved from one orbital location to another as a group, in order to perform multiple missions of covering different areas on the earth, or in the earth's atmosphere, with radar. The entire satellite cluster operates at orbit altitudes of 600-1000 km with high inclinations of 50-90 degrees. Figure 1 depicts the mission.

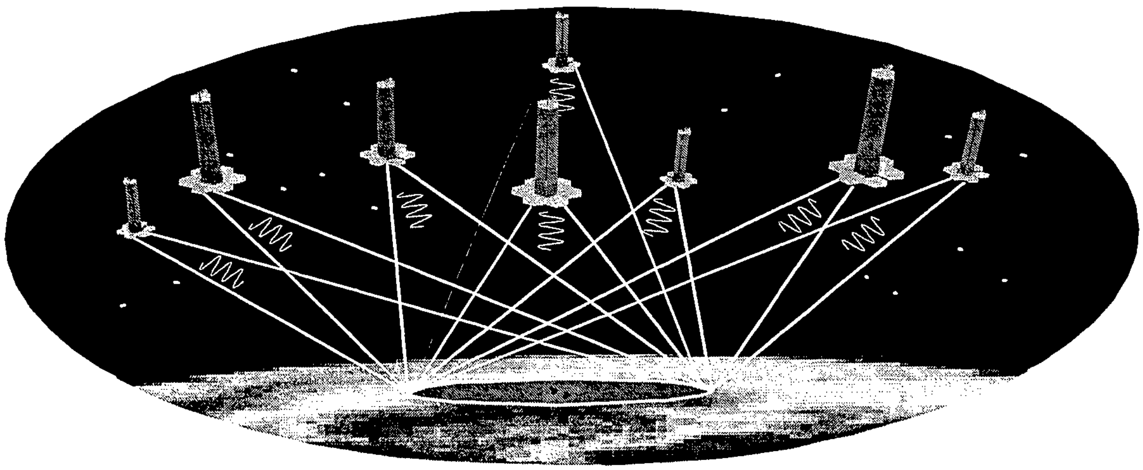

Figure 1. Distributed SAR Mission Illustration of ISL Based Satellite LAN

ISL related operations and constraints from the following mission entities are now described:

1. Spacecraft Subsystems
   a) Communications And Data Handling (C&DH)
   b) Navigation
   c) Payload
2. Orbital Effects
3. Launch Vehicle Constraints
   a) Mass
   b) Volume
   c) Deployment
4. Program Design Constraints
   a) Structure
   b) Power
   c) Cost.

2.4.2 Spacecraft Subsystems

Although spacecraft are composed of a number of subsystems, the range of ISL operational impacts is encompassed by the operations and characteristics of three major subsystems: C&DH, navigation and the payload.

2.4.2.1 Communications and Data Handling

The C&DH subsystem of the distributed, satellite based SAR mission provides downlink spacecraft payload telemetry reporting, subsystem status telemetry reporting, satellite cluster/LAN time synchronization and C^2. Two downlinks exist. One downlink is via ground stations to a geostationary Earth orbit (GEO) communications satellite transmitting to each of the spacecraft in the satellite cluster or LAN. An additional downlink using the radar payload antennas to transmit information is also provided. The ISLs are decoupled from the communications uplink and downlink subsystem in that ISLs are not used for interfacing to the ground station or other data recipients below the satellite cluster. The C&DH subsystem is a separate subsystem from the ISL subsystem.

2.4.2.1.1 Payload Telemetry

The radar payload provides radar return processing results to the ground via the C&DH ground links. The radar processing occurs onboard the satellites and hence only a small portion of the collected radar return data is downlinked as payload data. Since ISLs are not used for downlinking payload data, further payload telemetry details are beyond the scope of this operations concept. ISLs may be able to make use of an interface to the payload telemetry data within the C&DH subsystem to perform ISL optimizations and error handling.

2.4.2.1.2 Status Telemetry

Subsystem status information, including payload subsystem status data, e.g., voltage levels, temperatures and setting indicators, is also downlinked via the C&DH subsystem. Such data is typically in the kbps range. Once again, since ISLs are not used for subsystem status telemetry downlinking, further details are not required. ISLs may be able to make use of an interface to the subsystem status telemetry data within the C&DH subsystem to perform ISL optimizations and error handling.

2.4.2.1.3 Time Synchronization

The ISL in conjunction with the C&DH system is expected to provide satellite position and ranging information for the radar data processing component of the payload subsystem. The position and ranging data may be derived from internal spacecraft clocks augmented or backed up with Global Positioning Satellite (GPS) transmissions. The ISL system must therefore be able to receive and decode carrier phase differential GPS transmissions or be able to receive differential GPS data from another subsystem such as the C&DH subsystem. Differential GPS data and payload data transmissions between satellites via the ISLs are to be used to derive 20 ps satellite cluster timing synchronization and 3 mm satellite relative position determination. The high accuracy time synchronization and ranging requirements (20 ps and 3 mm) derive from the need to synchronize the clocks and payload data processing onboard all satellites. The timing and ranging calculations are envisioned to be performed by the ISL subsystem and passed on to the C&DH subsystem. Ranging data is also used to support navigation subsystem collision avoidance operations.

2.4.2.1.4 Command And Control

C^2 consists mainly of uplinked commands for mission positioning and mission execution timing. Commands for subsystem components are also available to the extent permitted by the subsystem design. Payload uploads, such as new processing algorithms or processing algorithm modifications, may be accomplished via the C&DH C^2 subsystem or via ISLs. If payload uploads are not accomplished via C^2 operation, then ISLs would require a payload upload operational capability, discussed under payload operations. Initiation, suspension, resumption and termination of payload uploads and downloads are expected to be C^2 operations. C^2 data rates are nominally in the kbps range. Since ISLs are not used for C^2 uplinking, further C^2 details are not required. ISLs may be able to make use of an interface to the C^2 portion of the C&DH subsystem in order to perform C^2 uplink backup operations and error handling.

2.4.2.2 Navigation

The navigation subsystem is responsible for position/attitude determination and control. Since the mission operation requires the cluster of eight satellites to be within a minimum of several meters to a maximum of 5000 km, the range accuracy to each neighbor in the cluster is desired to 3 mm. To achieve this high degree of accuracy for collision avoidance and cluster formation preservation, the navigation subsystem will most likely transmit position related information between satellites. ISLs would be used to transmit this information. The navigation subsystem can perform satellite attitude control to ± 5 degrees, with attitude determination to 0.02 degrees. A data rate of several kbps is therefore assumed to be transmitted by the ISLs for cluster management. In addition, ISLs are assumed to be used to transmit high accuracy position data between all the satellites just before and during mission execution time. Because of the importance and accuracy requirements of high

accuracy position data, a bit error rate of 10^{-12} for transmission of pre-mission position data is a desired ISL operational mode with a bit error rate of 10^{-6} being a minimum. The satellite geometry is changing fairly slowly, and under the influence of largely predictable forces. During non-operational (radar) periods, cluster management ISL communications could be spaced minutes apart. During radar operation, the geometry updates must be more frequent since the error allowance is much smaller. Rough calculations show that orbital perturbations cause relative drifts of 50 m over 4 hours. However, these perturbations are predominantly due to known effects and could be predicted/tracked easily, thus relaxing the update requirement. As a result, for a 3 mm position knowledge requirement, ISL position updates may be required to be transmitted every second. With a 10-20% mission duty cycle, the ISL pre-mission position data transmission operation is expected to make up only 1% of ISL transmissions.

Either extrapolation of ISL transmission of differential GPS position data or ISL transmission radio frequency (RF) phase shift information will be used by the ISL subsystem to calculate timing and position accuracy. If timing data is output by the ISL to the navigation, C&DH and payload subsystems, an ISL timestamp function with enough bits to provide picosecond accuracy will be required. Additionally, the timestamp extraction by other subsystems must be with less than 20 ps variation, or jitter. If the ISL subsystem outputs only a timing signal, then a 20 ps timing signal interface must be provided between the ISL and other subsystems, such as the navigation subsystem. If position data is output by the ISL, then other subsystems such as the navigation, C&DH and payload subsystems, will require an ISL position data interface. Using the ISL to derive time synchronization and position determination for all spacecraft navigation and payload operations will necessitate a number of ISL internal and interface functions and will restrict ISL implementation options.

The navigation subsystem can be used to yaw steer the satellites. Such a navigation subsystem operational capability assures that all satellites present the same structural view to all satellites at all times. With yaw steering, all satellites can always see the same side or view of all other satellites. For ISL operation, always presenting the same view to all other satellites can facilitate the placement and pointing operations of link transmitter antennas, waveguides, or lasers.

The navigation subsystem is responsible for maintaining the satellite cluster management and LAN physical topology. The cluster of satellites may be arranged in a ring, star, torus or other topology where no one satellite is allowed to have ISL operational modes, capabilities or equipment different from any other satellite. The SAR mission cluster is typically arranged in a ring topology. Cluster or LAN topology affects ISL operation in a significant manner. As long as the payload required data rates for the ISLs can be met, an ISL friendly topology, within the navigation subsystem's operational tolerances, should be selected for mission operations. Friendly topologies making for less difficult ISL operations and implementations include coplanar orbits, circular orbits, non line-of-sight (LOS) obscurations, yielding low Doppler shifts and relative velocities. Choosing an ISL friendly topology simplifies ISL operation and implementation.

2.4.2.3 Payload

The radar payload on each satellite within the cluster operates at 10 GHz. The radar has two modes. In one mode, ground moving target indication (GMTI), the bandwidth is 20 MHz and in the synthetic aperture radar (imaging) mode the bandwidth is 500 MHz. In the latter mode, little exchange of data between satellites is expected. The driving case for the ISL throughput is expected to be GMTI mode. During radar return reception, the receive signal is digitized, not keeping track of separate pulses. In the worst case, where all satellites receive all the radar return data from all other satellites, ISL communication would require transmitting the following number of bits on each ISL:

500 MHz/radar pulse (radar intermediate frequency - IF bandwidth) x Nq (Nyquist sampling rate of 2 samples/Hz plus
10% margin for 2.2 samples/Hz) x D (digitization bits/sample).

ISL processing at one satellite would have to accommodate the reception of N-1 (total number of satellites minus 1) times the number of bits above:

$$(N\text{-}1) \times P \text{ pulses/sec} \times 500 \text{ MHz/pulse} \times 2.2 \text{ samples/Hz} \times D \text{ bits/sample}.$$

Table 1 summarizes a number of ISL operational data rate possibilities.

Table 1. Distributed SAR Payload ISL Data Rate Calculations

Payload ISL Data Rates					
Radar Payload Bandwidth (MHz)	Nyquist Sampling Rate Nq (samples/Hz)	Digitization levels = 2^D bits D (D bits/sample)	Total # of Bits/sec transmitted by each satellite (Mbps)	Number of satellites minus 1 (N-1)	Total number of ISL bits received at each satellite (Gbps)
GMTI Mode					
500	2.2	8	8800	2	17.6
500	2.2	8	8800	7	61.6
500	2.2	12	13200	2	26.4
500	2.2	12	13200	7	92.4
Imaging Mode					
20	2.2	8	352	2	0.704
20	2.2	8	352	7	2.464
20	2.2	12	528	2	1.056
20	2.2	12	528	7	3.696

As can be seen from Table 1, ISLs must support a high transmission data rate and an even higher data reception rate. Assuming that the distributed SAR radar algorithms on each satellite can be developed to require only a portion of complete radar data from the other satellites, then the ISLs between satellites need to transmit much less than the worst case 528 Mbps. Assuming a best case of a minimum of 100 Mbps of radar data transmission for algorithm processing, this bounds the ISL transmission operation at between 100 - 528 Mbps. These rates still require N-1 times the amount of ISL receive capacity, or a range of 700 Mbps to 3.7 Gbps. Given that this mode of payload data transmission is 10-20% of the total ISL operational time (duty cycle or mission execution time), then the ISLs must have a peak capacity of 100 - 528 Mbps for transmission and 0.7 - 3.7 Gbps for reception that must be sustained for 10-20% of the life span of the satellites. Payload data transmissions are required to have a bit error rate of less than or equal to 10^{-6}.

In conjunction with radar payload processing, SAR algorithm processing distribution impacts ISL operation. If the amount of data to be transmitted via ISLs for SAR algorithm processing is reduced by sending different subsets of radar return data to different satellites, the ISL link operation must include addressing operations.

One broadcast transmission per satellite could contain all the radar return data from that satellite, with different pieces of the data identified or tagged for different recipient satellites. In this case, a single ISL from each satellite would broadcast all data from that satellite in one message to all other satellites. In this case, the ISL transmission rate would need to be the lowest processing algorithm's data reception time limit, minus some propagation delay and processing time, divided by the sum of all the number of bits required by all other satellite algorithms. Figure 2 depicts broadcast ISL operation within a cluster of eight satellites.

Seven simultaneous transmissions per satellite could be made to transmit different data to different satellites. Each transmission would only require a maximum of 1/7 of the total data and data rate of a single ISL transmission. Possibly seven transmitters and possibly seven receivers may be required. A single transmitter and receiver could implement seven different virtual channels through the use of Wave Division Multiplexing (WDM) in optical systems, or through the use of seven different correlation codes in CDMA RF systems.

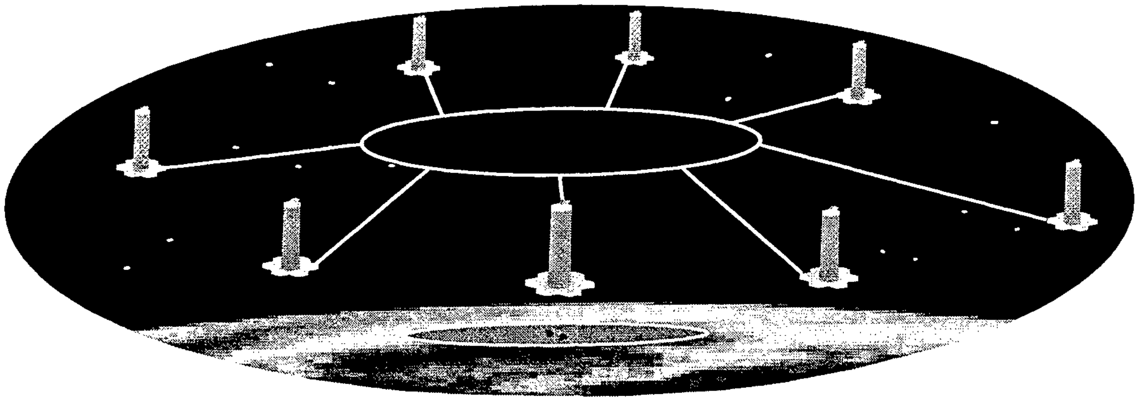

Figure 2. Broadcast ISL LAN Cluster Operation

Seven sequential transmissions could be made to transmit different data to different satellites. The data rates would either have to be seven times that of a single, broadcast ISL transmission rate, or the algorithm processing time would have to be extended by a factor of seven. Figure 3 depicts a completely connected ISL topology with seven transmissions per satellite, yielding the maximum number of 28 bi-directional links.

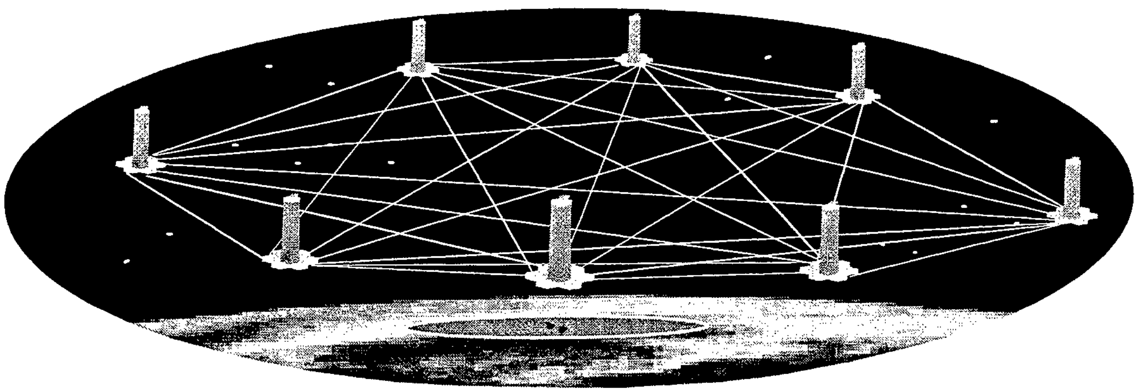

Figure 3. Distributed SAR Mission Maximum Number Bi-Directional ISL Operation

With a satellite cluster where every satellite is connected to every other satellite, there are N(N-1) maximum number of unidirectional ISLs, where N is the number of satellites. With eight satellites, there are 8 x (8-1), or 56 ISLs. If each link is bi-directional, there are N(N-1)/2, or 28 maximum bi-directional ISLs.

Finally, combinations of the previous three transmission operational modes could be employed for ISL operation. For example, one broadcast transmission could be made to supply the data to three other satellites and another transmission could be made (either simultaneously or after the first) to provide the data to the remaining four satellites. Depending upon the data and timing needs of the algorithms on different satellites, ISL operation may be composed of

1. A single transmission of all data to all other satellites (broadcast mode)
2. Multiple simultaneous transmission to all other satellites (point-to-point mode)
3. Multiple sequential transmission to all other satellites (point-to-point mode)
4. Combinations of the previous three (e.g., multicasting mode).

Case 1 gives rise to the least number of ISLs. Only eight broadcast type ISLs are required for all eight satellites to communicate with one another, where all data from each satellite is contained in one transmission, regardless of whether all the data in a single ISL is used by a receiving satellite. Cases 2

and 3 give rise to the maximum number of ISLs, either 28 bi-directional or 56 unidirectional links. Case 4 can give rise to a number of ISLs between case 1 and cases 2 and 3, 8-56 uni-directional or 8-28 bi-directional links. Acknowledgments, error handling and other protocol handshaking replies to messages can either be piggybacked unto the next message transmissions, radar data transmissions or non radar data messages such as navigational or C^2 messages, or sent as separate messages.

It is also possible to alter SAR algorithm processing based on the operational limitations of the ISLs, as opposed to altering ISL operation based on SAR limitations. The most technologically challenging to implement, whether distributed SAR algorithm processing or ISL, will drive the operation of the other.

Payload uploads, such as new processing algorithms or processing algorithm modifications, could be accomplished via ISLs. The ISL receivers could be used to transmit payload uploads. If this is the operation for payload uploads, the ISLs would have to be able to accomplish command validation, verification and authentication, or be able to interface to the C&DH system for performance of these functions. In addition, ISL receivers would have to be interoperable with payload upload transmission equipment. ISL receive components would have to have additional interfaces to payload subsystem components used for storing processing algorithms. Since the ISLs are used some of the time for low rate navigation collision avoidance and orbit maintenance data transmissions, simultaneous reception of payload uploads with navigational data seems a likely mode of ISL operation. If the C&DH system is used to perform payload uploads, the ISL would not require simultaneous ISL and ground link operation. ISL interoperability with upload equipment would also not be required. ISL to payload subsystem interfacing would also be simplified.

During 80-90% of non radar data transmission operations, payload operations require only occasional status information and perhaps processing algorithm uploads. Payload status information is not transmitted or received via the ISLs. As mentioned in the Status Telemetry section above, ISLs may be able to make use of an interface to the payload subsystem status telemetry data to perform ISL optimizations and error handling.

2.4.3 Orbital Effects

Orbital altitudes, shapes and orbit inclinations have an impact on ISL operations, particularly when combined with satellite LANs or clusters where the satellites to be linked are in different orbital planes or in non-circular orbits. At LEO altitudes of 600 - 1000 km and at high orbital inclinations of 50 -90 degrees, all eight satellites travel at relatively high velocities to one another unless constant changes in velocity (delta-V) are made. The distributed SAR mission uses spacecraft thrusters sparingly to maintain a tight cluster spacing of a nominal 100 m separation between satellites.

Intersatellite range rates of ≤ 1 m/s are to be maintained. Given such low intersatellite distances and range rates, ISL receivers and transmitters do not have to deal with high relative velocities and large amounts of Doppler shift (or variations in Doppler shift) in data transmissions.

Using yaw steering with the low relative velocities and Doppler shifts, in conjunction with the close spacing of the satellites in the cluster, it may be possible to use fixed antennas or optical components for ISL transmitting and receiving. The satellite cluster would act as if all satellites are in a single orbital plane, making for the case of intraplane communication where the satellites will always be in the same position relative to one another. The LOS paths between these satellites will not change angle and length significantly avoiding the added complications of interplanar communications and non circular orbits: a) high relative velocities between the satellites, b) tracking control problems as antennas must slew around and high Doppler shifts. This can be considered a result of Kepler's second law, where equal areas of arc of the orbital plane are swept out in equal times. With elliptical orbits, a satellite would see the relative positions of satellites ahead and behind appear to rise or fall considerably throughout the orbit, and controlled pointing of the fore and aft intraplane link antennas would be required to compensate for this. For the distributed SAR mission, all eight satellites are assumed to behave as if they are in the same orbital plane. Sparingly using thrusters to make for a satellite cluster with circular orbit characteristics, avoids ISL complications arising from non circular orbits.

As the cluster of satellites moves in a group from one mission location to another, orbital mechanics and navigation subsystem limitations may cause one satellite to obstruct the LOS between two other satellites. With the potential orbital effect of LOS obscuration, a number of new potential ISL operations may be required. The ISL subsystem may have to have an interface to the navigation system to avoid LOS obscuration or to be notified of impending LOS obscuration. The ISL may be required to sense obscuration, through bit error rate increases or loss of link connection. ISL operations may require routing of messages through other satellites in order to reach a satellite not in LOS. ISL operations may have to include a redundant non LOS transmission mode and communications equipment for times of LOS obscuration. If LOS obscuration data transmission outages are not acceptable, then ISL operation may have to be via non LOS transmissions, e.g., RF as opposed to optical.

ISL operation and implementation is very much dependent upon orbital effects, particularly orbit types and inclinations, and LOS obscuration. Assuming that the distributed SAR mission cluster has circular type orbits, interplanar communications only and no LOS obscurations, fixed antenna and optical ISL operations can be employed.

2.4.4 Launch Vehicle Constraints

The launch vehicle chosen for lifting the satellites into orbit places a number of physical restrictions on the ISL subsystem which can severely effect the implementation options, and hence the operation, of ISLs.

2.4.4.1 Mass

Mass restrictions include a total satellite mass of ≤ 100 kg. Of that 100 kg, a maximum of 5 kg have been allocated for the ISL subsystem operation and implementation.

2.4.4.2 Volume

Volume inside launch vehicles is limited. The desired launch vehicle, stowed, volume of each satellite within the cluster is approximately 0.3 m^3. Of this volume, ≤ 0.02 m^3 is allocated for the ISL subsystem.

2.4.4.3 Deployment

Satellites can increase their volume over their launch vehicle volume through deployment of expandable structures and components after separation from the launch vehicle. Restrictions exist to limit the maximum size of even deployed satellites. Orbital speeds, slewing rates, payload and subsystem operational characteristics and other factors limit the deployed size of the distributed SAR satellites to approximately 4 m^3.

Given an expansion volume from 0.3 m^3 in a stowed launch vehicle configuration to a deployed, operational volume of 4 m^3, the implication for ISL operation is that the ISL subsystem must accommodate compression or collapsing for launch and expansion for deployment. Assuming a final deployed satellite volume and shape as depicted in Figure 4, the ISL subsystem can have an expansion factor of about 20 in height, with a shape that conforms to that of the satellite's shape.

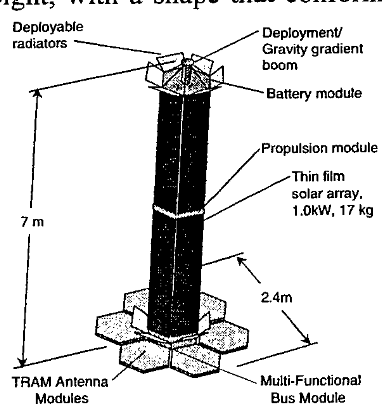

Figure 4. Deployed Distributed SAR Satellite Volume and Shape

A size and shape of 4 m in height, 1.2 m in width and 1.2 m in breadth, is therefore a reasonable operational constraint for deployed ISL operation.

2.4.5 Program Design Constraints

A number of SAR program factors, such as pre-existing conditions (e.g., use of development standards, Federal Communications Commission - FCC regulations, etc.), organizational issues, safety (e.g., collateral damage to other satellites), risk and cost management, and political factors, give rise to an additional set of restrictions on ISL operations and implementations. Three such program design constraints have the bulk of ISL operational impacts: structure, power and cost.

2.4.5.1 Structure

The deployable nature, multifunctional structures, smart mechanisms, thin film photovoltaics, micro-electro-mechanical components and advanced electronics packaging of the distributed SAR mission satellites influence ISL operation and implementation choices. ISL operations cannot damage or weaken the structure. For example, as a deployable, mechanical structure, high slewing rates of a large ISL link antenna would not be acceptable.

2.4.5.2 Power

Power limitations necessitate a power budget for the ISL subsystem. A power budget of $\leq$ 20 W has been allotted for ISL operation. The ISL cannot contaminate the electrical ground of the payload or other subsystem electronics.

2.4.5.3 Cost

Cost limitations have been placed on the ISL subsystem. A cost of $\leq$ \$300K, per ISL subsystem in quantities of 300 units has been levied on the ISL subsystem. Operational limitations for the ISL subsystem will arise as a result of cost limitations restricting implementation options.

2.4.6 ISL Operations

ISL operations arising from other mission entity operations, described in previous sections, are summarized in this section and additional ISL operations are described. The main ISL operations arise out of the need to support distributed SAR payload algorithm processing. This is emphasized through the use of a separate C&DH subsystem for payload and status telemetry downlinking, and C^2 uplinking and downlinking. An interface between the C&DH and ISL subsystems would provide for potential ISL operations to back up the C&DH downlink and uplink operations. A possible ISL and C&DH operation of sharing components between the ISL and C&DH system may be an operational mode used to assure ISL operation with ground link hardware, or to provide a degraded mode of ISL operation.

The most weighty ISL operation is payload data transmission on ISLs. Data rates for payload data transmission on ISLs are in the range of 100 - 528 Mbps, with a single satellite faced with receiving this number of bps from each of the other satellites for a total ISL receive rate of 0.7 - 3.7 Gbps. This payload data rate accounts for 10-20% of ISL operation. ISLs are expected to be transmitting navigational data (including differential GPS data) providing a constant bit rate data stream of several kbps.

Whether the ISL transmission carrier and signal phase delays or ISL differential GPS calculations and data transmissions are used by the ISL subsystem to calculate timing and position accuracy, interfaces to other subsystems using timing and position information need to be provided. If timing and position data is output by the ISL to the navigation, C&DH and payload subsystems, an ISL data insertion and interface function with enough bits to provide picosecond and millimeter accuracy will be required. Additionally, the data extraction by other subsystems must be with less than 20 ps variation, or jitter. If the ISL subsystem outputs only a timing signal, then a 20 ps timing signal interface must be provided between the ISL and other subsystems, such as the navigation subsystem. Using the ISL to derive time synchronization and position determination for all spacecraft navigation and payload operations will necessitate a number of ISL internal and interface functions and will restrict ISL implementation options. Since cluster management and potentially

GPS navigational data is constantly transmitted over the ISLs, payload data insertion and extraction, and timing and position determination will have to be performed simultaneously.

Payload uploads might be via ISL operation. The ISL subsystem would have to be able to accomplish command validation, verification and authentication, or be able to interface to the C&DH system for performance of these three command functions. ISL receivers would have to interoperate with payload uplpad source transmission equipment and interface to payload subsystem components for storing processing algorithms. ISLs would have to have a dual receive mode where transmission from other ISLs and payload uploads could be received simultaneously.

2.4.7 Additional ISL Design Constraints

Additional ISL design constraints provide additional ISL operational characteristics. For any mission, ISL operation cannot interfere with payload operations. As a necessity for the SAR mission, ISL operation cannot interfere with the radar receivers. This provides an operational constraint for ISLs to have interference with radar receivers of ≤ 30 decibels relative to 1 W (dBW) out of the radar band of 10 GHz ±500 MHz and ≤ -210 dBW in the radar band of 10 GHz ±500 MHz. This would rule out virtually all ISL RF operation near 10 GHz. ISL operation shall adhere to standard EMI/EMC levels for all electronic equipment for interference with other spacecraft subsystems and ISL operation.

With a minimum number of eight and a maximum number of 28 (bi-directional) ISLs operating simultaneously, ISL transmissions must not interfere with one another. In the case of broadcast ISLs, non interference implies an ISL operational mode of being able to separate seven other satellite transmissions from one's own transmission. In the case of multiple ISL transmissions per satellite, an ISL receiver in one satellite must be able to identify the links addressed to this satellite from the links addressed to other satellites. When every satellite has an ISL to every other satellite, link address selection is not a required operation. In addition, with a fully interconnected LAN communications topology, every satellite is only one link away, avoiding the need for routing messages through one or more satellite to reach the intended recipient. ISL routing operations would only be required if LOS obscuration makes direct ISL connection impossible.

The useful life of the payload radar data is numbered in days, implying a need for ISL transmission security in the form of encryption, transmission encoding, e.g., frequency hoping, Code Division Multiple Access (CDMA), or transmission power limitations such as optical or spread spectrum (i.e., CDMA) operation. ISL transmission security needs to only provide protection to the degree of requiring another party more than 72 hours to break the protection scheme and obtain the data. However, breaking the ISL security scheme once must not lead to breaking the ISL security method in less time on subsequent security violation attempts. If ISLs are used to communicate C^2 messages or commands, whether spacecraft subsystem or payload commands, such ISL message transmissions require secure ISL operation. ISL security for C^2 messages requires ISL operation such that the C^2 commands cannot be extracted during the course of the mission life of the entire satellite cluster. Recording valid ISL C^2 messages and playing them back into ISL receivers by unauthorized parties must also be protected against. ISL C^2 transmissions need the command authorization, validation and verification set of operations.

It is not expected that intentional or unintentional jamming occur in the ISL frequency band. Should a jammer operate in the ISL channel frequencies, the mission may be jeopardized and therefore some form of ISL jamming protection should be included in ISL operation.

Since radar data formats and definitions are known to all recipients before ISL operations begin, there is no need for higher layer communication protocols to be part of ISL communications protocol operation. Link error handling and security operations will be part of ISL operation. Data compression may be an ISL characteristic, depending upon ISL data rate limitations and radar algorithm processing needs. If ISL data rates are unable to be met within technology and design constraints, then ISL data rates can be reduced via data compression. Radar data may not be compressible enough for existing compression algorithms to warrant the ISL resource expenditure required to perform compression and decompression. Radar algorithms may not be able to tolerate the time delays of compression and decompression ISL operations.

ISL communications should be initiated automatically by cluster or LAN formation flying control and radar payload operational mode. The navigation subsystem may provide information to the ISL subsystem to initiate ISL operations if the ISL is not currently active. This may require an ISL preemptive operational capability, if other ISL transmission or test operations are in progress at the time of radar data transmission initiation requests. The ISL may need to sense formation flying control initiation through internal means, such as noting an increase in navigation data transmissions or noting the transmission requests for particular types of navigational commands or data. Radar, or payload operations could be communicated through interfacing with the radar or other spacecraft subsystems by way of receiving notification of radar operations. The ISL subsystem could detect current or impending radar operation through completely independent means such as increased noise levels in ISL receivers.

Each ISL, whether one or more per satellite, should be able to be controlled and tested individually, through ground command or self-test. Individual control includes an ISL operation of routing a command for satellite A in a particular way to satellite B. Individual control and test mode operations are therefore part of ISL functionality.

For all ISL operations and implementations, a technology extrapolation to the level of the year 2003 is allowed. Planning on what should be available in the year 2003 somewhat eases ISL operational and implementation restrictions. A number of additional design constraints may surface during the course of ISL development and implementation.

3.0 TECHSAT 21 SATELLITE LAN ISL REQUIREMENTS

The requirements document is the single source of all the binding conditions on any implementation of a system of interest. The system of interest is a set of ISLs, an ISL system, used in a satellite LAN or satellite LAN-like application. This requirements document defines the characteristics of ISLs used to link a number of satellites into a single virtual satellite in order to achieve the satellite mission objectives. This requirements document provides a means to communicate the inputs, outputs and physical constraints of ISLs in the context of planned and foreseeable satellite missions. The requirements document provides a single source of system requirements for organizations, individuals and systems involved with ISL system specification, development and test.

3.1 Purpose

The purpose of this requirements document is to define and document the set of ISL requirements for an actual, planned satellite mission, TS21, and to serve as the requirements source for evaluating wireless communication technologies and defining recommended ISL implementations capable of conducting planned and foreseeable space missions. Additional uses for the requirements document include evaluating future proposed ISL implementations, performing cost and risk tradeoffs and gaining user community acceptance of ISL implementations. The requirements document also serves to define the ISL system boundaries.

A secondary purpose of this ISL requirements document is for a wide range and number of satellite missions with satellite LAN-like interconnections to make use of the documented ISL requirements. This ISL requirements document provides for a wide range of ISL applications through the definition of a technologically stressing set of ISL requirements for an actual, planned satellite mission, TS21. High data rates, spacecraft subsystem support, stressing volume, weight, power and time delay/processing restrictions, etc., should allow a wide range and number of satellite missions to make use of this ISL requirements document for the above stated purposes.

3.2 Scope

The scope of this requirements document includes ISL characteristics and constraints arising from payload, C^2, navigation and other spacecraft subsystem operations involving or otherwise impacting ISL operations. The scope is further narrowed to a satellite mission using eight satellites operating as distributed, space based radars, linked to form one large, high resolution virtual satellite SAR. Design and launch segment constraint impacts on ISL characteristics are included. Computer-Human Interface (CHI) characteristics and their corresponding requirements are not specified since ISLs are an almost completely automated spacecraft subsystem with little or no human or manual control functions and operations.

Requirements validation, verification and testing are outside the scope of this document. However, requirements validation and verification are a critical part of providing an ISL satellite subsystem that performs all needed operations in the required manner. Requirements validation and verification can be performed through satellite program review of the requirements specified in this document. Revisions to the requirements arising from satellite program office review can be incorporated into a revised, validated and verified ISL requirements document. Requirements testing has been addressed to the extent that all requirements have been defined in such a manner as to allow testing through analysis, simulation or actual tests. An effort has been made to not define requirements that cannot be tested.

3.3 Approach

The requirements are identified as statements specifying the capabilities and characteristics that the ISL system shall have. The requirements are decomposed into one requirement per requirement statement. Individual requirements can be viewed as an answer to a question about the ISL system.

The ISL requirements are derived from one main source, the ISL Operations Concept, defined in the previous section. Secondary sources of requirements were also used: existing documentation used in defining the Operations Concept [C99, G99], technical interchanges between relevant personnel [TI99a-g] and the SBIR Program solicitation for this effort [DoD99.1].

In order that the defined requirements possess the necessary requirement qualities of Institute of Electrical and Electronics Engineers (IEEE) Standard 830-1998 "IEEE Recommended Practice for Software Requirements Specifications" and to facilitate electronic requirements analysis via Computer Aided System Engineering (CASE) tools, the following template is used to document ISL requirements in this document.

1. ID
   This field assigns a unique numeric requirement identifier.
2. Requirement
   This field provides a synopsis of the requirement.
3. Category
   This field classifies the requirement into one or more of the following categories: Functional, Data, Interface, Operational, Constraint, or Other. If more than one keyword is given, the first is considered the primary category of the requirement and the others give secondary associations.
4. Priority
   This field assigns a degree of necessity to the requirement as mandatory, optional or an idea for further development.
5. Uncertainty
   This field quantifies the likelihood of the requirement changing, with a 10 defined as shall not change and a 1 defined as certain to change.
6. Attribute_Other
   This field specifies optional, additional requirement attributes via attribute keywords such as: Internal, External, Conflict and Quantitative.
7. Source
   This field specifies one of six sources of the requirement: the Operations Concept document [M99], documentation used in defining the Operations Concept [C99, G99], technical interchanges between relevant personnel [TI99a-g] or the SBIR satellite LAN contract solicitation [DoD99.1]. Implied or derived requirements have one of the six sources of direct requirements listed as their source.
8. Reference
   This field cites a specific page and paragraph in the June 1999 Satellite LAN ISL Operations Concept document as a reference for further requirement details.
9. Identified_By
   This section records who the identifier of the requirement.

The template includes requirement categories and attributes. A category is simply a rough division or classification of the requirement which has an important place in the requirements identification process. The categories are chosen with a view towards the application of the ISL requirements in the later steps of the systems engineering methodology, design, development and test. When analysts return to this document with specific problems in mind (e.g., the construction of a data dictionary or conceptual design), they will find the requirements conveniently sorted (e.g., data requirements are in a separate category). Requirements may not fit completely in one category. In that case, it is necessary to decide what the primary category is and assign the requirement to it. The requirement may also be given a secondary category assignment. One may search the requirements database by category for requirements of interest. The categories used for requirements specification in this document are:

1. Functional
   Requirements about what the ISL system shall do are listed under this category.
2. Data
   Requirements specifying details about information, what must be produced, stored, processed, or interpreted. Requirements concerning data storage, access methods, error detection, distribution, security, protection and data syntax - format and type definitions are also listed under this category.

3. Performance
   Quantitative requirements about any aspect of ISL system performance, including how fast, how often, what detail or resolution, capacity reserves, etc., are listed under this category. Requirements concerning data input or output devices (payloads, other satellite subsystem data to be input or output via ISLs, etc.) and their performance requirements, including data volumes and rates are also listed under this category.
4. Interface
   Requirements regarding connections or data exchanges between pairs of entities are listed under this category. External interfaces to other satellites, ground systems and spacecraft subsystems are also listed under this category.
5. Operational
   Requirements regarding how the ISL system is going to be used (orbital constraints, etc.) are listed under this category. Requirements concerning the interaction of the user with the ISL system are outside the scope of this document but could be placed into this category.
6. Constraint
   Requirements concerning restrictions imposed by: pre-existing conditions, organizational impacts to be minimized or avoided, ease of use, schedule constraints, use of COTS equipment, FCC regulations, safety (e.g., collateral damage to other friendly satellites or satellite missions), ISL system protection, audit trails, maintainability, configuration and risk management (e.g., use of development standards from IEEE, American National Standards Institute - ANSI, etc.), ISL system fault handling and fault recovery, and non data performance considerations (e.g., weight, volume and power constraints) are all listed under this category. This category includes legal and political requirements (e.g., centralized vs. distributed control).

The categories are broad requirement classifications. Requirement classification attempts to assign requirements to more narrow, more specific groups or classes. The template therefore includes requirement attributes. Attributes further classify requirements into smaller groups. Attributes facilitate requirements validation, verification, analysis and testing by guiding analysts to the relevant requirements. In addition, attributes reduce the amount of information that must be exchanged between analysts and personnel in requirements related meetings. The attributes used for requirements specification in this document are:

1. Internal
   This attribute applies to requirements or data that are internal to the ISL system with no effect (e.g., levies no implied or somewhat hidden requirements) on other spacecraft or ground subsystems.
2. External
   This attribute applies to requirements or data that have an external to ISL source, sink or impact (e.g., levies direct, implied or somewhat hidden requirements) on other spacecraft or ground subsystems.
3. Conflict
   This attribute applies to requirements where another requirement identified with this attribute has a potential conflict with this requirement.
4. Quantitative
   This attribute applies to requirements that can be quantified and is especially interesting from the standpoint of performance (e.g., response time and capacity measures).

3.4 ISL Requirements Matrix

The following pages contain the ISL requirements in table format, defined according to the template specified above.

Table 2. TS21 Requirements

	TS21 ISL REQUIREMENTS							
ID	The ISL system shall:	C	P	U	AO	SRC	REF	BY
1	transmit radar payload data at a rate up to 100 Mbps for a maximum of 20% of on orbit time to two other satellites	P	M	10	Q	TI99g		AFRL
2	receive radar payload data at a minimum rate up to 100 Mbps for a minimum of 10% and a maximum of 20% of on orbit time from two other satellites simultaneously	P	M	10	Q	TI99g		AFRL
3	synchronize satellite cluster ISL clock times to allow satellite cluster ranging determinations on the order of 3 mm (e.g., within 20 ps)	P	M	10	I,Q	M99,TI99f	p4,pa2	AFRL
4	provide satellite cluster ranging information for 3 mm)satellite position accuracy determination with the use of ISL external spacecraft position bounded knowledge (e.g., GPS)	F,D	M	10	I,E,Q	M99,TI99g	p5,pa2	AFRL
5	have a known repeatable data latency through its system	P	M	10	I	TI99e		AFRL
6	have a loop-back (transponder or echo) mode with known latency in the loop	F,P	M	10	I	TI99e		AFRL
7	transmit satellite position information at a rate not to exceed once per minute during non radar operation	D,P	M	3	Q	TI99b		AFRL
8	transmit satellite position information once a second for 20% of the time during (radar operations)	D,P	M	8	Q	TI99b		AFRL
9	calculate link bit error rates	D	M	10	I		p10,pa1	MITL
10	transmit satellite position information with bit error rate of 10^{-12}	D,P	M	10	Q,I		p5,pa1	AFRL
11	attempt to compensate for satellite position information bit error rates greater than 10^{-12}	F,P	M	10	Q,I		p5,pa1	MITL
12	transmit radar payload data with bit error rate of 10^{-6}	D,P	M	10	Q,I	DoD99.1		MITL
13	attempt to compensate for radar payload data transmission link error rates greater than 10^{-6}	F,P	M	10	Q,I	DoD99.1		MITL
14	perform ISL link optimizations to include bit error rates, transmit power and transmission time	F	M	10	I	M99	p3,pa3	MITL
15	perform ISL error handling	D	M	10	I	M99	p3,pa3	MITL
16	determine loss of links or link connections	F	F	5	I	M99	p10,pa1	MITL
17	operate over distances up to 5000 km	D,P	M	10	I	M99	p2,pa3	AFRL
18	perform data compression and decompression on transmissions to and from other satellites	F,D	M	10	I	M99	p13,pa5	MITL
19	transmit to satellites in any direction nominally in a plane derived from stable solutions of Hill's equations	M	O	5	I,C	TI99e	p5,pa3	MITL
20	operate in the presence of LOS obstruction between the sending and receiving satellite	O	F	5	I,C	M99,TI99e	p10,pa1	MITL
21	function normally in the presence of a 70 dBs relative to 1 W (dBW) jammer operating in the 10 GHz ± 500 MHz operating band of the radar	D,P	M	10	I	M99	p13,pa4	AFRL
22	function normally in the presence of a 70 dBW jammer operating in the ISL channel frequencies	D,P	F	5	I	M99	p13,pa4	MITL
23	provide data transmission security to a level requiring a minimum time of 72 hours to recover the data by unauthorized entities with a projected 2003 technology level	D,P	M	7	I,Q	M99	p13,pa3	MITL
24	employ a data transmission security scheme whereby breaking the security once must not lead to breaking the security method in less time on subsequent security violation attempts	D,P	M	5	I,Q	M99	p13,pa3	MITL
25	route messages through other satellites in the cluster in order to reach the destination satellite	O	F	5	I	M99	p10,pa1	MITL

Table 2. TS21 Requirements (continued)

	TS21 ISL REQUIREMENTS							
ID	The ISL system shall:	C	P	U	AO	SRC	REF	BY
26	provide message routing to other satellites via specific address specification	O	F	5	I	M99	p14,pa3	MITL
27	provide message routing to other satellites via specific route specification	O	F	5	I	M99	p14,pa3	MITL
28	prioritize requests for service from external subsystems and entities	F	M	10	E,I	TI99f		MITL
29	preempt current link operations by terminating or suspending current operation and initiating a different link transmission	F	M	7	I	M99	p14,pa2	MITL
30	have each satellite's ISL subsystem controllable independent of other satellite ISLs	F	M	10	I,E	M99	p14,pa3	AFRL
31	have each satellite's ISL subsystem controllable via ground command	F,I	M	10	I,E	M99	p14,pa3	AFRL
32	perform a satellite group self-test automatically	F	M	10	I	M99	p14,pa3	AFRL
33	perform an individual satellite ISL subsystem self-test automatically	F	M	10	I	M99	p14,pa3	AFRL
34	perform a satellite group self-test upon ground command initiation	F,I	M	10	I,E	M99	p14,pa3	AFRL
35	perform an individual satellite ISL subsystem self-test upon ground command initiation	F,I	M	10	I,E	M99	p14,pa3	AFRL
36	have all ISL systems with equal functionality	F	M	10	I	M99	p5,pa4	AFRL
37	interface to the payload subsystem	I	F	2	E	M99,TI99e	p8,pa4	MITL
38	initiate radar data link transmissions to other satellites without ground command upon impending or start of radar operation	O,I	M	10	I,E	M99	p14,pa2	AFRL
39	have access to payload telemetry data	I	O	3	E	M99	p3,pa3	MITL
40	input data and commands from the payload subsystem	I	F	2	E	M99,TI99e	p9,pa2	MITL
41	output data and commands to the payload subsystem	I	F	2	E	M99,TI99e	p9,pa2	MITL
42	transmit satellite position information while transmitting radar payload data	F,I	F	5	I,E	M99	p4,pa4	MITL
43	be able to receive and transmit navigation data while receiving and transmitting radar payload data	F,I	F	5	I,E	M99	p9,pa1	MITL
44	receive payload data while transmitting satellite position data to other satellites	F,I	F	5	I,E	M99	p9,pa1	MITL
45	employ payload command and data reception protection to avoid unauthorized payload access	F	F	1	I	M99	p13,pa3	MITL
46	employ payload command and data transmission protection to avoid unauthorized payload access	F	F	1	I	M99	p13,pa3	MITL
47	interface to the Command & Data Handling (C&DH) subsystem	I	F	2	E	M99,TI99e	p8,pa4	MITL
48	input data and commands from the Command & Data Handling (C&DH) subsystem	I	F	2	E	M99,TI99e	p8,pa4	MITL
49	output data and commands to the Command & Data Handling (C&DH) subsystem	I	F	2	E	M99,TI99e	p8,pa4	MITL
50	interface to the navigation subsystem	I	M	10	E	M99,TI99f	p14,pa2	MITL
51	initiate operation based on cluster or LAN formation flying control without ground command	O,I	M	10	I,E	M99	p14,pa2	AFRL
52	allow the navigation subsystem to initiate ISL operation	F,I	M	10	E	M99,TI99f	p9,pa2	MITL
53	have access to other subsystem status telemetry data	I	O	3	E	M99	p3,pa4	MITL
54	indicate to the other spacecraft subsystems that there is some ISL communications activity	F,I	F	5	E,I	TI99f		AFRL
55	not interfere with payload operations	C	M	10	E	G99		AFRL
56	not interfere with spacecraft operations	C	M	10	E	G99		AFRL
57	cause no collateral damage to other spacecraft	C	M	7	E	M99	p11,pa2	MITL

Table 2. TS21 Requirements (continued)

	TS21 ISL REQUIREMENTS							
ID	The ISL system shall:	C	P	U	AO	SRC	REF	BY
58	comply with standard electromagnetic interference/electromagnetic compatibility (EMI/EMC) levels for all electronic equipment for interference with other spacecraft subsystems	C	M	10	I	G99		AFRL
59	abide by all applicable FCC regulations for radio frequency and optical energy transmissions	C	M	10	I	M99	p11,pa2	MITL
60	output energy at ≤ -210 dBW within the 10 GHz) ± 500 MHz operating band of the radar payload	C,P	M	10	I,E,Q	M99	p13,pa1	AFRL
61	output energy at ≤ 30 dBW outside of the 10 GHz ± 500 MHz operating band of the radar payload	C,P	M	10	I,E,Q	M99	p13,pa1	AFRL
62	operate at altitudes of 600 - 1000 km	O	M	10	I,Q	M99	p9,pa3	AFRL
63	operate at orbital inclinations of 50 - 90 degrees	O	M	10	I,Q	M99	p9,pa3	AFRL
64	operate at orbital satellite range rates of ≤ 1 m/s)	O	M	10	I,Q	M99	p9,pa3	AFRL
65	have a mass ≤ 5 kg	C	M	10	I,Q	M99	p10,pa4	AFRL
66	have a stowed (inside launch vehicle) volume ≤ 0.3 m3	C	M	10	I,Q	M99	p10,pa4	AFRL
67	fit within the 1.2 m diameter by 0.45 m high stowed volume envelope	C	M	10	Q	TI99c		AFRL
68	have antenna locations less than 2.8 m away from the center of the spacecraft	C	M	10	Q	TI99c		AFRL
69	not be in the hemispherical volume below the radar payload antenna	C	M	10	Q	TI99c		AFRL
70	have a power consumption of ≤ 20 W	C	M	10	I,Q	M99	p11,pa4	AFRL
71	have a cost of ≤ $300K when produced in a quantities of 300	C	M	10	I,Q	M99	p11,pa5	AFRL

ID Requirement Identifier
C Category
- F Functional
- D Data
- P Performance
- I Interface
- O Operational
- C Constraint

P Priority
- M Mandatory
- O Optional
- F Idea for further development

U Uncertainty
- 10 Shall not change
- 1 Certain to change

AO Attribute_Other
- I Internal
- E External
- C Conflict
- Q Quantitative

SRC Source
- M99 Operations Concept document
- C99 Documentation used in defining the Operations Concept
- G99 Documentation used in defining the Operations Concept
- TI99a-g Technical interchanges between relevant personnel
- DoD99.1 SBIR satellite LAN contract solicitation

REF Reference
- p Page
- pa Paragraph

BY Identified_By
- MITI MiTech Incorporated
- AFRL AFRL Personnel

3.5 Operational System versus Flight Experiment Requirements

The previous table contains the ISL requirements for the TS21 ISL Operational System for the 2008 time frame. A TS21 flight experiment is planned for launch in the 2003 time frame. The flight experiment is a proof of concept for the TS21 operational mission. Three satellites without real-time radar data processing capability comprise the flight experiment as opposed to eight satellites with real-time radar data processing capability for the operational system. As a result, the ISL requirements for the flight experiment are a subset of the ISL requirements for the operational

system listed in Table 2: ISL Requirements. At this point in time, the main differences in ISL operational versus flight experiment requirements are that no payload data transmissions are required, and the timing synchronization and position determination accuracy are relaxed to what can be achieved in time for the flight experiment.

3.6 Requirements Validation and Verification

Requirements validation and verification are a critical part of providing an ISL satellite subsystem that performs all needed operations in the required manner. Requirements validation and verification can be performed through satellite program personnel review of the requirements specified in this document. Requirements categorized with priorities of "O" (optional) and "F" (idea for further development) need to be validated and verified as "M" (mandatory) requirements or deleted. Any requirements with an attribute of "C" (conflict) need to have their conflicts with other requirements eliminated. Requirement conflicts can be resolved through the elimination of conflicting requirements or modification of the requirements to remove any conflicts. Program office requirements validation and verification process results should be incorporated into a revised, validated and verified ISL requirements document.

4.0 ISL ARCHITECTURE DEFINITION

The ISL architecture validates the key technology to be employed, assesses the feasibility of meeting the ISL requirements and defines the top level design for implementing an ISL.

4.1 Purpose

The purpose of the ISL architecture definition is to identify and specify an implementation architecture and key components that provide for a future detailed design and implementation meeting the requirements identified earlier. The architecture definition also serves to evaluate existing and emerging wireless technologies, and to define the ISL system boundaries.

4.2 Scope

The scope of the ISL architecture definition is limited to defining an architecture to a high level. Hardware and software components are only identified and defined to the level necessary to lead to an ISL detailed design capable of meeting the requirements.

4.3 Approach

Wireless physical transmission and media access methods, hardware and software applicable to satellite LANs and ISLs were analyzed. Existing, in development and possible future development communication technologies and components were evaluated for use in implementing an ISL for an operational space flight planned in the year 2003. Heavy emphasis was given to COTS technology and components in order to meet the short development schedule of the TS21 program.

Wireless physical transmission and media access methods and components applicable to satellite LANs and ISLs examined and evaluated included RF and optical (laser) versions of CDMA, time division multiple access (TDMA), frequency division multiple access (FDMA) and for optical transmission, the equivalent of FDMA - WDM. Combinations of these three main candidate technologies are also possible. Multi-carrier CDMA, or orthogonal frequency-division multiplexing (OFDM) and wideband CDMA (W-CDMA) methods of CDMA are promising examples of additional wireless optical transmission methods examined applicability for satellite LAN ISL implementation [DGNS98, HP97, HWNC98].

CDMA or spread spectrum technology was chosen as the best candidate for an ISL architecture and implementation. Spread-spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information. The bandwidth spread is accomplished by means of a code that is independent of the data. A synchronized reception with the code at the receiver is used for despreading and subsequent data recovery. Traditional ways of separating signals in time (i.e., TDMA), or in frequency (i.e., FDMA) are relatively simple ways of making sure that transmissions are orthogonal and non interfering. However, in CDMA, different users or transmissions occupy the same bandwidth at the same time, but are separated from each other via the use of a set of orthogonal waveforms, sequences, or codes. There are two main types of CDMA: direct-sequence spread spectrum (DSSS) and frequency-hopping spread spectrum (FH-SS). Hybrids of combinations of the two CDMA types also exist. Of the different types of CDMA, direct sequence CDMA (DS-CDMA) was chosen as the technology of choice for an ISL. DS-CDMA requires a simpler transmitter and receiver by using a bit pattern code to provide the bandwidth spreading rather than using frequency hopping of the carrier frequency in a pseudo-random fashion to perform the bandwidth spreading. DS-CDMA provides all characteristics for the required high data rate, low bit error rates, interference, low power, security and Doppler shift requirements of satellite LANs and ISLs. CDMA technology also met the necessary SBIR requirement of a technology that can be commercialized. A high data rate CDMA transmission system is of immense commercial interest. Approximately 50 vendors of satellite and terrestrial wireless communications link hardware, including Motorola, Qualcomm, Alcatel, Marconi, Sirius, Hyundai and Hughes were contacted. The emphasis on ISL link transmission hardware vendor research and discussions came down to CDMA versus FDMA components. Optical technologies and components were not available in the foreseeable future with the required tracking and pointing, LOS obscuration operations and other characteristics (i.e., meeting the other ISL requirements). Component suppliers for Motorola,

Raytheon, Qualcomm and Globalstar CDMA products such as Xilinx, Texas Instruments and Sirius appear to have a number of components that be used as is or with minor modifications for a 100 Mbps ISL in space. CDMA encoding and decoding application specific integrated circuits (ASICs) for satellites are in development and on track for space qualification in eight months time that will allow ISL link rates to be available in 20 Mbps increments.

4.4 ISL Antenna Placement

ISL antenna placement will make for some shadowing, areas where ISL signal transmissions will be blocked by the satellite structure. If satellites are placed in relation to one another where the ISL RF radiation LOS is blocked from one satellite to another satellite (from an ISL transmit antenna to an ISL receive antenna), the ISL could cease to function due to insufficient signal strength at the receiver. Using the formulas and drawing in Figures 5 and 6, some noteworthy calculations can be made.

Given ISL antenna placement:
2 cm high (approx. 1 cm circumference) isotropic ISL antenna, operating at about 1 GHz, placed at the top of the TS21 satellite, communicating with another TS21 satellite 10 m below the first satellite.

Results:
23.6 dB loss of ISL transmit signal strength from the satellite on top to the satellite on the bottom just from the shadowing caused by the structure of the satellite above blocking the signal to the satellite below. This does not include radiation free space losses.

Given ISL antenna placement:
2 cm high ISL antenna, operating at about 1 GHz, placed 5 cm (2 inches) from the outer edge of the radar panel on top of the radar panel, communicating with another TS21 satellite 10 m below the first satellite.

Results:
13 dB loss of ISL transmit signal strength from the satellite on top to the satellite on the bottom just from the shadowing caused by the structure of the satellite above blocking the signal to the satellite below. This does not include radiation free space losses.

$$L_{ke}(v) = -20\log\frac{1}{\pi v\sqrt{2}}$$

$$v = h'\sqrt{\frac{2(d_1'+d_2')}{\lambda d_1' d_2'}} = \alpha\sqrt{\frac{2d_1' d_2'}{\lambda(d_1'+d_2')}}$$

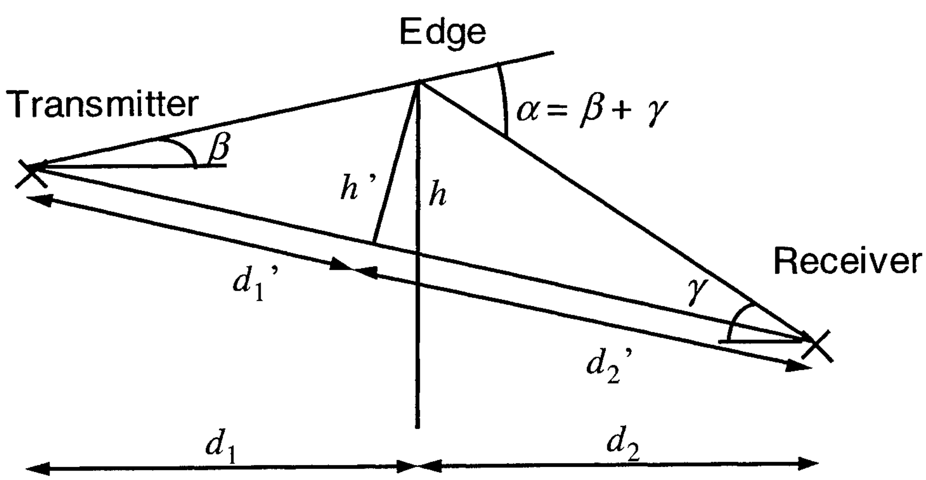

Figure 5. Knife Edge Signal Loss (L_{ke}) Calculation for ISL Antenna Shadowing [S99]

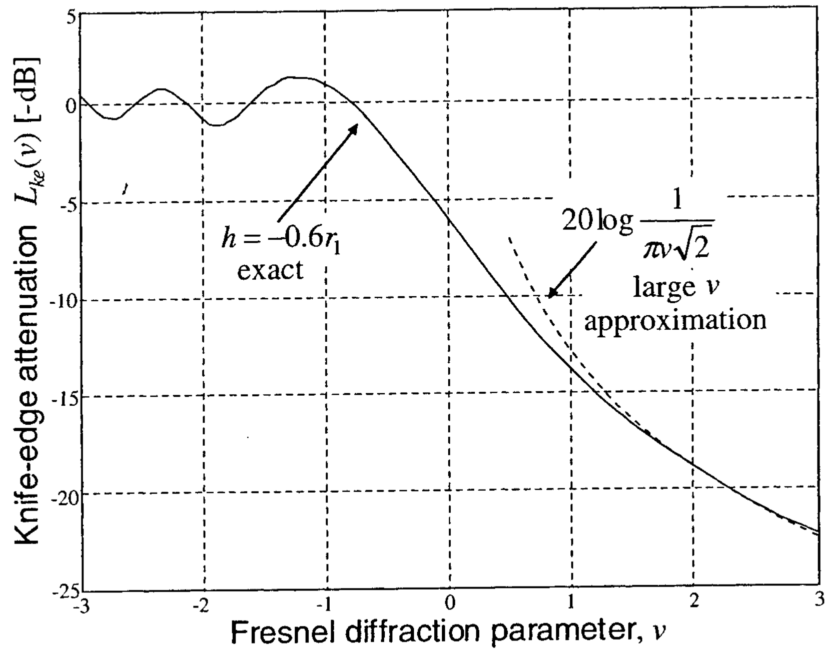

Figure 6. Shadowing Caused ISL Signal Loss vs. Distance in Shadow Area (v) [S99]

What these calculations communicate is that ISL antenna placement makes a significant difference in the amount of energy received at the ISL antenna of another satellite when shadowing occurs from the structure of either the transmitting or receiving satellite obstructing the RF path between ISL transmit and receive antennas. Operational restrictions, such as not placing satellites within ISL transmission shadow areas, need to be traded off against ISL antenna placement options.

4.5 ISL Architecture/High Level Design

Figure 7 illustrates MiTech's high level ISL design that performs all functions, 100 Mbps payload data transmission, 3 mm distance calculations and 20 ps timing references, with ranging and timing derived from the received CDMA transmissions.

Data from the satellite payload or other subsystems is made available to the ISL processor for transmission through the ISL to other satellites. Payload data or other subsystem data received via the ISL is also taken in and made available to the ISL processor for routing to the appropriate satellite subsystem. Data is transmitted using 64-Quadrature Amplitude Modulation Differential Quadrature Phase Shift Keying (64-QAM-DQPSK) in order to conserve bandwidth and in order to provide rapid enough phase changes for picosecond timing and millimeter ranging calculations. A Walsh 64-bit spreading code is used as the CDMA code. The other components for transmitting are fairly standard. The receiver contains the same components in reverse order. This design should yield an RF system that can operate at low GHz, near 1 to 5.7 GHz, with a bandwidth of 1.6 times that of the data rate. If the data rate were 100 Mbps, then the bandwidth required would be 160 MHz. Operating at 1 - 5.7 GHz makes possible the use of COTS analog RF antennas, amplifiers, modulators, etc. At a 160 MHz bandwidth, COTS analog-to-digital (A/D) and digital-to-analog (D/A) converters can also be utilized. The extensive use of COTS components greatly reduces the costs and risks of the ISL system.

Two other important details are the use of a high frequency pilot tone for synchronization of the receiver and transmitter, as well as for extracting 3 mm distance calculations and 20 ps timing references from the received pilot tone phase [CDMA1-7]. The pilot tone may have to be modulated by a bit pattern long enough for phase differentiation to the 20 ps level. The concept is to use a high frequency pilot tone synchronization signal, with a wavelength of twice that of the required distance measurement requirement. A frequency with a wavelength of twice the desired

ranging/distance measurement is all that is required since measurement accuracy is possible to within 1/2 that of the smallest measurement unit. The principle is the same as using a ruler with 1/4 inch as the smallest unit of measure. With such a ruler one can measure to within 1/8 of an inch, or within 1/2 of the smallest unit of measure. Using 1/2 of the measurement of the 50 GHz wavelength yields a 3 mm distance. For example, a 50 GHz tone has a wavelength of 6 mm. Half of the wavelength of a 50 GHz tone yields a 3 mm position reference point, relative to the transmitter (to the other satellite). Detecting the wavelength position (6 mm length) of the received pilot tone and the phase of the received pilot tone, and comparing these two measurements with the phase of the incoming 64-QAM-DQPSK data and reference pilot tone phase and wavelength position, should yield a 3 mm distance to transmitter calculation. The CDMA Phase and Pilot Tone Logic in Figure 5 makes the wavelength pilot tone and phase measurements in order to output a 3 mm relative distance to transmitter and a 20 ps (using the 50 GHz half wavelength) timing reference. A 50 GHz tone has a wavelength time of 1/f, or 20 ps. Using the measurement principle of measuring within 1/2 of the smallest unit of measure, a 20 ps timing reference is possible.

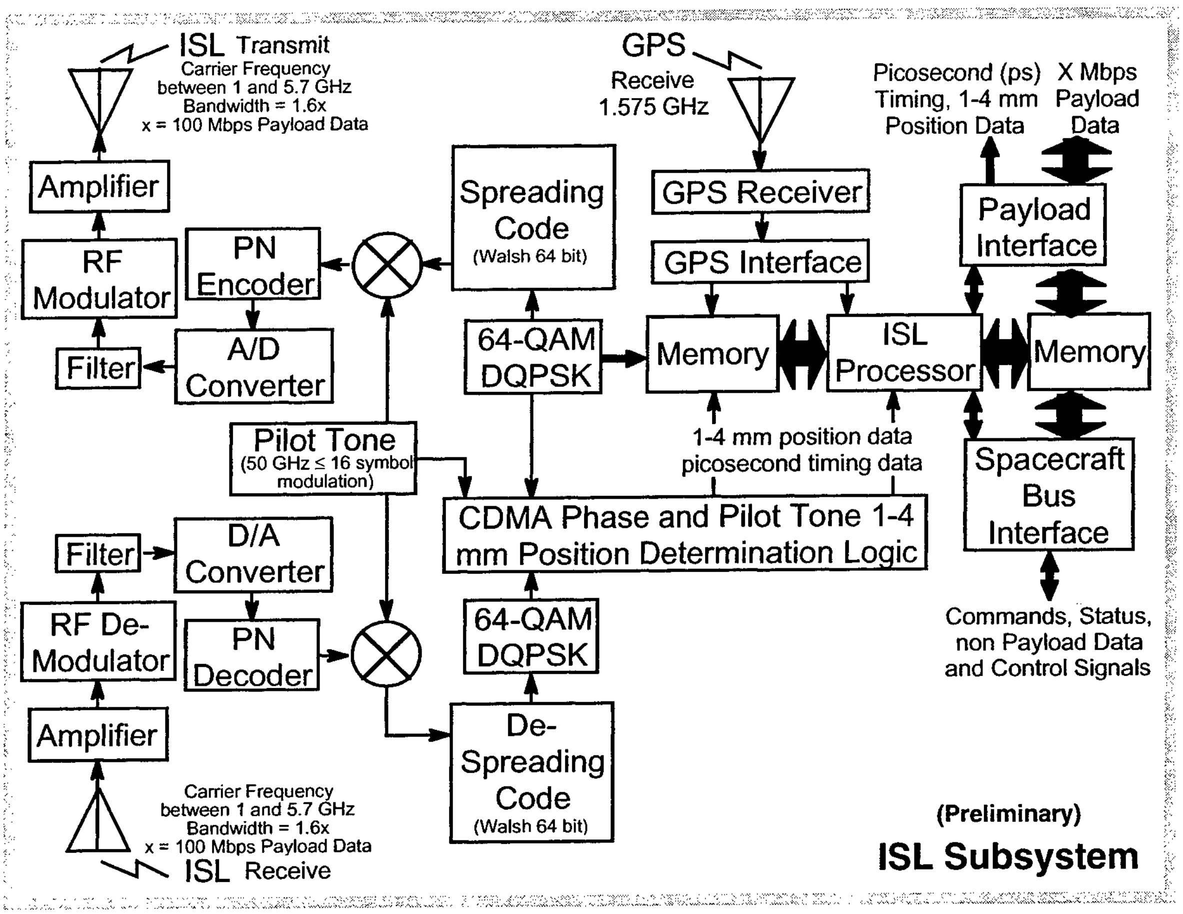

Figure 7. Integrated CDMA ISL System with Picosecond Timing and Millimeter Ranging

The advantage of the approach illustrated in Figure 7 is that the entire position determination functionality is integrated into one package, yielding the most power, volume and weight efficient implementation of the required ISL, ranging and payload timing functionality.

A standard (COTS) differential GPS receiver and antenna are used to provide absolute satellite position determination to within 2 cm. The output of the CDMA Phase and Pilot Tone Logic provides relative position accuracy to within 3 mm for the distance from satellite to satellite. Combining the ISL 3 mm relative position with the GPS 20 mm absolute position can yield the

required absolute satellite cluster position accuracy of 3 mm. The ISL 3 mm relative distance information is used to narrow the differential GPS derived position from 20 mm (2 cm) to 3 mm. No GPS data needs to be sent between satellites in order to derive the relative position of each satellite to within 3 mm.

The transmission of the payload data, subsystem command and status data, or formation flying data via the CDMA ISL link is sufficient to provide 3 mm position and 20 ps timing outputs. This ISL system is fully contained and requires no additional inputs in order to provide 3 mm satellite position and 20 ps payload timing.

Figure 8 is essentially the same CDMA receiver and transmitter, and associated 3 mm distance calculation and 10 ps timing reference derivation logic as in Figure 7. The major difference in the ISL system of Figure 8 are that the time reference source is not a GPS receiver, but rather a high resolution, highly stable rubidium oscillator from the payload subsystem, and that the GPS receiver and GPS position determination functions are located in a separate GPS subsystem.

Even in this case however, no separate GPS data needs to be sent from satellite to satellite in order to determine satellite position to within 3 mm or in order to provide 20 ps payload timing and synchronization signals. A standard differential GPS subsystem receiver could be used with the configuration in Figure 8, where the ISL processor integrates the GPS 2 cm position data with the CDMA ISL data to output 3 mm position and 20 ps timing and synchronization signals and data.

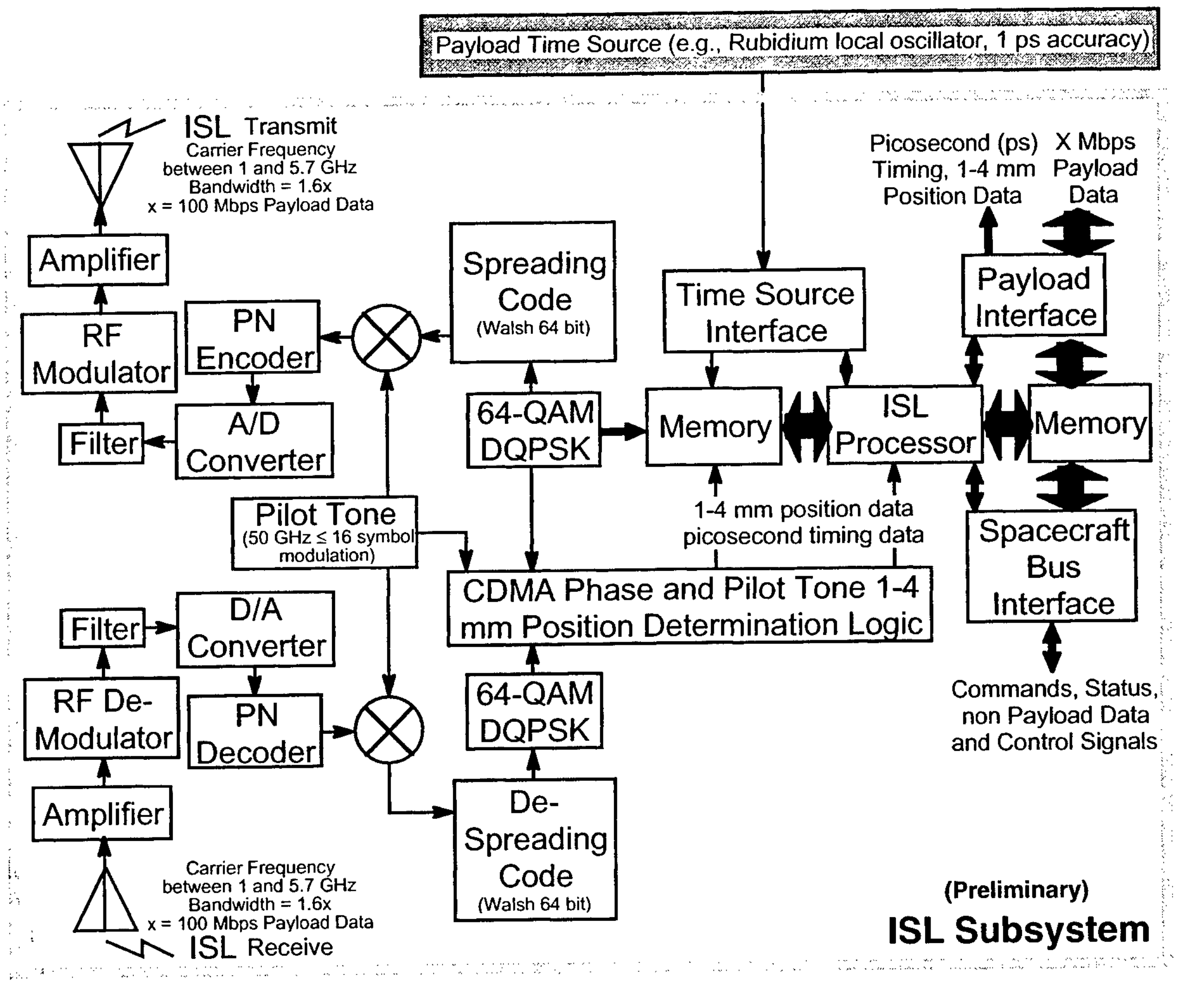

Figure 8. Separate CDMA ISL and GPS Systems with ISL Picosecond Timing and Millimeter Ranging Augmentation of GPS Position Calculation

The advantage the approach illustrated in Figure 8 is that the GPS functionality is separated from the ISL functionality. The two functions, GPS and ISL, can therefore be separated into two subsystems with independent developments, testing and integration schedules and locations.

Design and implementation of an ISL prototype were not part of this SBIR Phase I effort. However, based on the previous requirements, architecture definition and component availability (both near term and in time for a 2008 satellite launch), some top level design information can be determined. A flight ISL system is envisioned to look like the prototype implementation depicted in Figure 9.

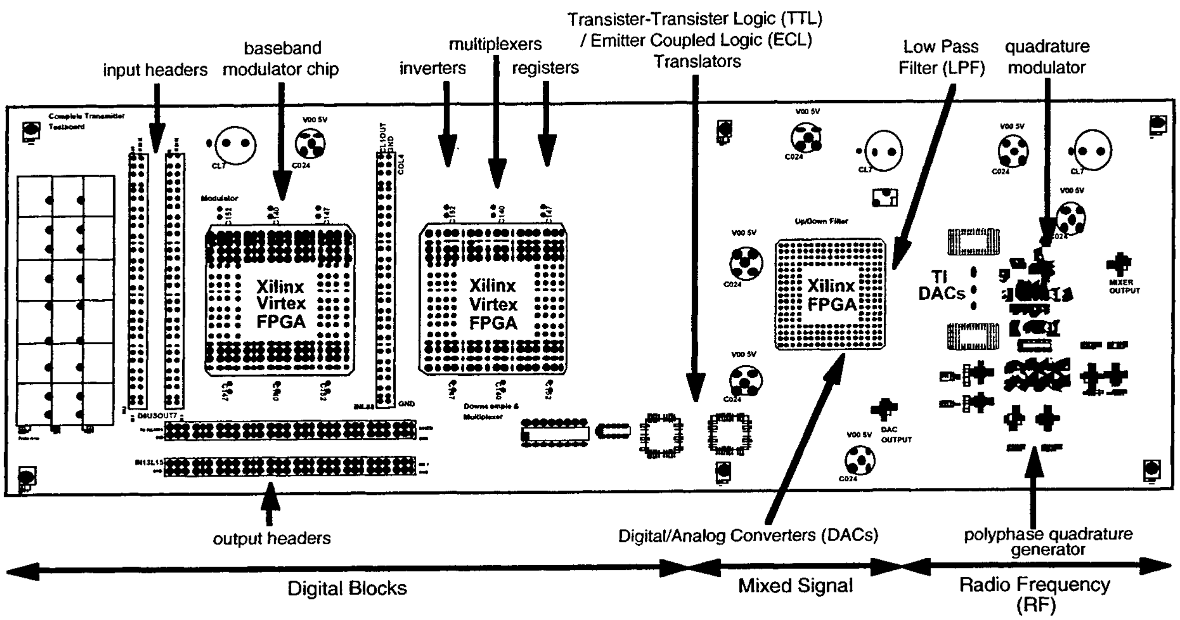

Figure 9. Prototype ISL Design

Field Programmable Gate Arrays (FPGAs), such as the Virtex-E series by Xilinx Inc., and the CommsDAC™ Product Family of A/D and D/A converters by Texas Instruments Inc. can provide close to 100% of all required functionality and electrical requirements. The XCV2000E FPGA device by Xilinx contains more than enough logic gates (≥ 2 million system gates) and high enough clocking speed to implement as much as possible of the CDMA receiver and transmitter in the digital rather than analog domain. Texas Instruments D/As and A/Ds such as the THS5661A, when concatenated together and used in parallel operation, can provide the necessary domain conversions for a 100 Mbps data rate DS-CDMA signal transmission and reception. 20 Mbps CDMA chips by Sirius Communications could also be used in the implementation if incremental data rate transmission were an important feature of the ISL. Low spreading rates through high symbol encoding (e.g., 64-bit QAM-DQPSK) are important in maintaining a transmission rate that is a reasonable multiple of the of the data rate (e.g., 1.6 - as in the proposed architectures of Figures 7 and 8). A CDMA low power design and implementation example that is very similar and applicable to an ISL implementation is presented in [SB99].

5.0 IDENTIFY AND ANALYZE WIRELESS SOFTWARE/HARDWARE COMMUNICATION PROTOCOLS

The communication protocols above the physical layer (including data link, network, transport and application) for the ISLs are identified and analyzed. Previous tasks specified the physical layer as a function of the available COTS CDMA RF transmission components. The physical layer DS-CDMA or DSSS, along with this task's data link layer protocol definition and specification, complete the entire communications architecture necessary for ISL communication. The Open Systems Interconnect (OSI) Reference Model (OSI-RM) representation of the entire communications model is depicted in Figure 10.

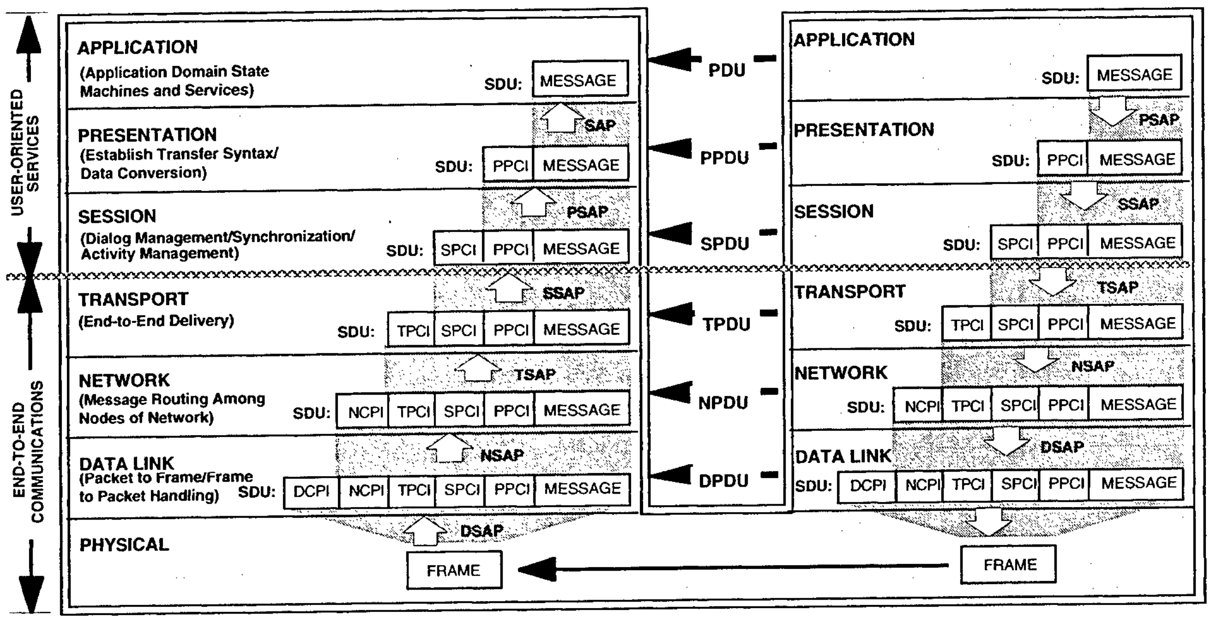

Figure 10. Open Systems Interconnection Reference Model for Communication

5.1 Purpose

The purpose of this task is to identify and specify the entire communications protocol architecture for the ISL subsystem.

5.2 Scope

Physical, data link layer and some form of application layer protocol functionality is required for any type of ISL communication. Due to the COTS nature of the ISL design, the physical layer protocol functionality will be determined by the RF COTS components selected for the ISL prototype and flight unit implementations. The hardware components selected for implementing a CDMA based RF ISL will include the physical layer and media access control communications protocol functions. The scope of identifying and analyzing ISL protocols is therefore limited to those protocols above the physical layer and the media access control portion of the data link layer.

5.3 Approach

The absolute minimum communications protocol architecture or protocol stack includes the physical layer, data link layer functionality and some form of application layer data exchange syntax and format specification. The data exchange syntax and format specification can be derived from the data link layer protocol specification if the data link layer specification includes data syntax and format specifications. A communications architecture composed of a Physical and Data Link Layer

protocol stack is therefore the minimum and hence highest performance communications protocol architecture available. All protocol functionality above the data link layer (network, transport, session and presentation layer) are optional and deemed as unnecessary overhead for ISL operation. Since the physical layer is dictated by the CDMA components, only the Data Link Protocol (DLP) needs to be specified.

The data link layer and application layer protocol candidates examined were IEEE, International Standards Organization (ISO), Instrument Society of America (ISA), Internet Engineering Task Force (IETF) existing and proposed protocols and standards (i.e., Request for Comments - RFCs) and custom implementations of data link and application layer protocols. Protocol candidates for consideration in this task included such protocol standards as HDLC, ATM, IP, TCP, UDP, XTP, application layer protocols such as the Manufacturing Message Specification (MMS - ISO 9506) and the Simple Network Management Protocol (SNMP - RFC 1157), and a complete protocol stack, ISA's SP-50. Modifications to these existing protocols and completely new protocols were also considered.

5.4 Protocol Requirements

In order to arrive at which protocol or protocols are best for an ISL implementation, communication protocol requirements are defined. Once requirements are defined, matching candidates to requirements reveals the optimum selections.

Utilization of ISLs for a TS21 space based, sparse synthetic aperture radar requires three top level functions of the ISLs: a) timing reference determination and synchronization, b) position or range determination and c) transfer of 100 Mbps or more of radar data between the satellites. With estimated timing needs to the 20 ps level and estimated position determination to the 3 mm level, along with Mbps data transfer, performance is the dominant criteria for identifying and specifying ISL protocols and their requirements.

The data link control protocol will have to provide the needed functionality (establish a reliable bit pipe from sender to receiver to include data syntax and format specification) and will have to meet five top level requirements:

1. Performance
   Minimize the protocol overhead in terms of hardware, processing time and throughput delay
2. COTS Interoperability
   Interoperate with available hardware and software
3. Quality of Service (QoS) functionality
   Provide the necessary error rate and data (radar, ranging and timing) services
4. Interface
   Provide a flexible and high performance with acceptable cost, weight, volume and power characteristics
5. Manufacturing
   Provide commercially acceptable cost, weight, volume, power and interface characteristics.

5.4.1 Performance Requirements

The performance of an ISL communications protocol stack can be defined in a number of ways. In most cases, link performance is defined as the percentage of the link bandwidth used for data transmission for a given error rate and signal to noise ratio. Performance can also be defined as the percentage of the link bandwidth used for data transmission for a given QoS. C^2 applications require higher QoS than data transmission applications. C^2 QoS requirements, such as in order delivery of error free command and position data packets, typically require higher forward error correction (FEC), Automatic Repeat Request (ARQ) and encoding transmission overhead than a data transmission which can tolerate lost, error containing and out of order data packets. Since the physical layer performance is dictated by the available CDMA components and therefore addressed in an earlier task, only the DLP performance needs to be specified.

For the ISL-DLP (ISLP), performance is improved significantly over existing High-Level Data Link Control (HDLC), Space Communications Protocol Standards (SCPS), Consultative Committee on Space Data Systems (CCSDS) and proprietary space link protocols through extension

of DLP functionality to include performance enhancing QoS functions. The main performance enhancing QoS functions are:

1. Adaptive header and data compression ratios and algorithms
2. Selective repeat ARQ (SR-ARQ) with multiple buffers
3. Variety of adaptive FEC algorithms selected according to application needs and link transmission characteristics.

The additional QoS capabilities of the ISLP eliminate the need for additional upper layer protocols through the use of the additional QoS services. The elimination of upper layer protocols provides another large performance benefit. The upper layer protocol implementation can affect the overall link data throughput performance more than all the QoS and other performance enhancing features of the data link protocol. In fact, the implementation of protocols used above the data link protocol affect the performance of the link more than all the data link protocol factors combined.

QoS service selection and implementation can greatly affect data link performance. A good hardware implementation can assure that additional QoS services and their execution do not limit data throughput to something less than the link transmission capacity.

Performance analyses and data is presented in Section 5.9: Performance. Sections 5.9.1.6 and 5.9.1.7 with their real world data measurements provide the basis for the recommendation that the ISL use only a data link layer protocol. The use of additional protocol functionality above the data link layer via a separate protocol is deemed to be extremely risky. It seems unlikely that an ISL implementation with an upper layer protocol can achieve 100 Mbps data transfer rates, 20 ps timing and 3 mm estimated position determination performance.

5.4.2 COTS Interoperability

COTS interoperability is defined as the ISL DLP's ability to work with the hardware and software available to implement the ISL link. Since the physical layer interoperability is dictated by the available CDMA technology, discussed in a previous task, only the DLP interoperability needs to be specified.

The new service extensions to HDLC are defined in such a way as to be interoperable with existing HDLC compliant implementations and with the HDLC standard. New services are added using the existing procedures and frame structure of the HDLC standard. All of the above service parameters are defined and selected using the existing content and format of the HDLC Information Transfer Frame (I-frame), Unnumbered Command Control Frame (U-frame), Supervisory Frame (S-frame) and Exchange Information Frame (XID-frame). The U-frame is used to convey that the ISLP version of HDLC is being used with the optional QoS extensions. The QoS function selection and implementation are conveyed in the beginning of the I-frame information or user data field. The XID-frame is used to confirm QoS selections for available resources and to set existing HDLC parameters, such as maximum information field length, window size and timers, to match the selected QoS options.

Together, the existing U, I, S and XID frames implement an extended ISLP that is interoperable with HDLC, provides additional services and additional performance. Interoperability with HDLC compliant protocols is felt to be a necessity for commercial applications of the new ISLP.

Interoperability with the SCPS and Internet TCP/IP and UDP/IP protocols is assured through the concept of encapsulation and compliance with the HDLC data link layer service specification. The entire Internet protocols can be encapsulated inside the ISLP user data field, preserving IP/TCP/UDP functionality and interoperability. If the network and transport protocol (IP/TCP/UDP) functionality is desired for some commercial application, these protocols can be used on top of the ISLP without modification.

Interoperability with the CCSDS protocols and existing space link systems is achieved through the use of the existing eight CCSDS protocol services: Internet, Path, Encapsulation, Multiplexing, Bitstream, Virtual Channel Access (VCA), Insert, and Virtual Channel Data Unit. With the use of the existing CCSDS services, a careful selection of the combination of ISLP functionality (especially the new, extended services) and CCSDS services is required in order to achieve reasonable

performance. Using the new ISLP in place of the equivalent, duplicated functions within CCSDS protocols would require modification of the CCSDS VCA and Virtual Channel Link Control (VCLC) data link protocols. Interoperability with CCSDS presently requires the overhead of CCSDS protocols. Proposing to the CCSDS committee to modify their VCA and VCLC protocols to provide the functionality of the new ISLP is an option that should be pursued if higher performance and CCSDS interoperability is desired.

With the use of an extended HDLC as the ISLP, interfaces can follow the ISO standards for interfacing between the data link and the physical protocol layers [ISO10022], and between the data link and network protocol layers [ISO8886] of the ISO OSI reference model [ISO7498]. The existing service interfaces support the new data link services. This may be a significant advantage for interfacing the ISL subsystem to other TS21 satellite subsystems. HDLC software and hardware implementation and testing support is readily available for a Real-Time Operating System (RTOS) and an Operating System Environment (OSE) link manager, both of which are likely to be employed by other TS21 subsystems interfacing to the ISL subsystem.

5.4.3 QoS Functionality

QoS functionality is defined as the set of communication link performance and functional parameters required to provide the necessary error rate and data (radar, ranging and timing) services. The communication parameters result from the negotiation of: a) services offered by the link protocols to: users, applications or systems and b) services requested from the link protocols by: users, applications or systems. The transmission link parameters of the protocol services define the QoS functionality. QoS functionality is therefore implemented through protocol services. Modifications or additions to existing protocol services may be made to a communications protocol to provide the QoS required by the communicating entities.

QoS services specify communication link properties such as performance (throughput and time delays), reliability and security. An application's QoS needs and requests, such as the preferred degradation path (e.g., higher data rate with higher error rate vs. lower data rate and lower error rate), are translated into link QoS services such as FEC algorithm and message transfer unit (MTU) size selection, which are protocol services. The QoS parameters and specifications may change during the data transmission. Since the physical layer communications functionality is dictated by the available CDMA components and therefore defined in an earlier task, only the DLP functionality is specified.

In the case of the ISLP, where the FEC, compression and all QoS services can be modified, turned off or on at the request of a link user or link performance optimization program, there is no QoS service which does not affect link performance. Table 3 summarizes the QoS functions proposed and defined for the ISLP. Any or all of the data link protocol functions in Table 3 can be selected for the ISLP. In the case where a function is not desired or performed outside of the ISLP (e.g., compression/decompression, encryption/decryption), the QoS function is simply not used. Any overhead associated with unused QoS ISLP functions is not incurred by ISLP processing.

The TS21 ISL will most likely utilize a maximum of three of the 21 defined QoS services: FEC, ARQ and possibly compression. Implementations of ISLP QoS functions are possible that do not restrict the performance of the link in terms of reducing the data throughput to less than that needed for real-time radar data transmissions. It is not necessary to restrict QoS services to rudimentary offerings.

5.4.4 Interface

An ISL communications protocol interface is the definition of the physical (e.g., electrical and optical) signal encoding, data syntax, format and protocol services (including invocation and termination).

An ISL communications protocol interface exists between: a) ISL subsystems on different TS21 satellites, b) the ISL subsystem and non TS21 satellite constellation communication sites such a ground station and c) the ISL subsystem and other subsystems onboard the same satellite. Potential TS21 ISL requirements include transmitting radar data to the ground and receiving commands, uploads, etc. from the ground. An ISL to ground interface is therefore a likely ISLP interface.

The requirements for the protocol interface are to provide a flexible and high performance with acceptable cost, weight, volume and power characteristics. There are two main categories of TS21 ISL interfaces: 1) transmission and 2) physical subsystem.

Table 3. The Existing HDLC Protocol is extended to include 21 QoS Functions

ISLP QoS FUNCTIONALITY	
QoS Function	**Range**
Throughput or Bandwidth	
1. Data packet (MTU) size	few bytes to Megabytes
2. Number of bits per second	User selectable to $\geq$ 100 Mbps
3. Rate (for consecutive packets)	User selectable
4. Segmented delivery	Yes or No
5. Flow control and congestion control	none to packet by packet
6. Compression	none to more than 100 to 1
Time	
7. Delay limits	milliseconds to hours
8. Response time	milliseconds to minutes
9. Jitter	milliseconds to seconds
10. Interstream synchronization	none to milliseconds
11. Expedited data (e.g., preempt)	none to prioritizing link queues
Reliability	
12. Data corruption threshold	many errors OK to no errors allowed
13. Data loss threshold	packet loss OK to no bit loss required
14. Replication of data	acceptable or not tolerated
15. Data delivery order	no order to specific order
16. Group delivery	no to all in group must confirm
17. Forward error correction (FEC)	none to 50% of total # of bits/second
18. Automatic repeat request (ARQ)	Go-back-N or selective repeat
Security	
19. Access security (e.g., fencing)	none to lengthy access codes
20. Data security (e.g., encryption)	none to 256 bit keys
21. Data unit manipulation	none to byte by byte

5.4.4.1 Transmission

The ISL communications transmission interface is the connection provided by the wireless transmission of CDMA encoded RF signals and includes the physical layer, data link layer and any other additional upper layer protocol interfaces. The interface between ISL subsystems on different TS21 satellites and the ISL subsystem and a ground station are transmission type interfaces. These interfaces include the physical, data link and any upper layer protocol interfaces. The physical layer interface is defined by the chosen CDMA RF transmission technology components and is defined in the previous task: ISL Architecture Definition.

The ISLP interface is the standard set of HDLC protocol services and their interfaces. All HDLC extensions, the set of TS21 ISL selectable QoS function extensions to HDLC, use the standard HDLC services, procedures and interfaces as defined in ISO 13239, 4335, 3309, 8886 and 10171. The interface for all possible HDLC extensions is depicted in a following section. No further protocol interfaces are required if the recommendation to use no additional protocols is followed.

Flexibility of the protocol interface is maximized at the physical layer through the use of CDMA and the CDMA inherent characteristics of pseudo-noise codes (for adding new links to the system) and RF spectrum sharing, and through the use of a QoS extension mechanism applied to the HDLC protocol, defining an international standard HDLC protocol interoperable ISLP. With the

QoS extensions, the ISLP provides a very flexible interface in that many aspects of the interface can be negotiated on a communication by communication basis. All the aspects of the communications protocol interface listed in Table 3 can be altered and set to optimize the specific communication interface.

The impact of the DLP on interface performance has already been discussed under the previous section. The selection of QoS options such as FEC algorithm, ARQ mechanism and compression can greatly enhance the performance of an ISL communications protocol interface without sacrificing the advantages of interoperability and implementation of an international standard DLP.

Cost, volume, weight and power characteristics of an ISLP based on an extended HDLC protocol have been discussed in the previous section on manufacturing. A communications protocol interface using only a data link layer protocol and using an existing standard (i.e., HDLC) as the basis for the DLP, provides the lowest cost, volume, weight and power combination while providing the necessary performance.

If additional upper layer protocols are used, the interfaces between HDLC (or whatever is used as the data link layer protocol for the ISLP) and any additional protocols must be specified and implemented.

5.4.4.2 Physical Subsystem

The ISL communications physical subsystem interface is the connection between the ISL subsystem and other subsystems onboard the TS21 satellite. This satellite subsystem interface is usually a physical connection such as a electrical or optical wires, cables, busses or LANs.

This interface is a communications protocol interface in the sense that the data syntax, format and transmission procedures must be specified. The physical, and possibly the data link and network layer protocols, are defined by the selected physical connection, such as an IEEE 1553 or IEEE 1014 Versa Module Eurocard (VME) bus. In the case of a physical connection where only the physical layer protocol is specified, for example RS-422. the data link layer protocol will need to be defined. In the extreme case where only wires or optical fibers are used, even the physical layer protocol will need to be specified. Although the definition of this interface is not a part of the internal ISL communications and hence not within the scope of this task, because this interface impacts the ISL subsystem, some recommendations are provided.

The optimum performance from an ISL standpoint would be to use the same or very similar DLP (i.e., HDLC) for the internal satellite ISL to other subsystem interface as is used for the DLP within the ISL subsystem, for communication between satellites. This would reduce ISL implementation costs (power, volume, weight and dollars) by not having to design and implement additional circuitry for an additional protocol. Performance would also be maximized by utilizing the fewest number of protocols, hence eliminating additional processing for protocol conversion and implementation functions. For a payload data rate of 100 Mbps, a physical connection with a greater than 100 Mbps transmission rate should be selected. This would eliminate VME and 1553 busses from the available options.

The selection of physical ISL to other onboard subsystem interface could include such criteria as available, standard COTS components, a data rate of $\geq$ 100 Mbps, a packet size optimized for radar data size (e.g., eliminating Asynchronous Transfer Mode - ATM and its 48 byte packets), and power, volume and weight. A potential candidate meeting all criteria, including HDLC support, might be the Myrinet LAN technology by Myricom Inc.

5.4.5 Manufacturing

Manufacturing requirements for an ISLP or any other layer protocol (e.g., network - IP, transport - TCP, or application - MMS) center on four requirements:

1. Cost
2. Weight
3. Volume
4. Power.

The manufacturing cost requirement is composed of two aspects, initial and recurring cost. Initial engineering costs of designing the first unit and engineering costs incurred as a result of design changes from the first production unit to the mass production are not included in manufacturing cost. Initial manufacturing cost is the amount of resources required to manufacture the first production unit. Recurring manufacturing cost is defined as the resources required to mass produce units. Facilities and tooling costs (clean rooms, sub-micron fabrication and test equipment), raw materials, component costs and their availability are the main factors determining manufacturing costs. Physical layer manufacturing is dictated by the available CDMA components and is addressed in an earlier task. Physical and DLP manufacturing are closely linked in that DLP manufacturing consists of implementing the DLP in some of the same hardware (e.g., FPGAs) that some of the physical layer (CDMA, etc.) functionality resides.

In the case of the ISLP, existing facilities and tooling can be used to produce the hardware based ISLP units. There are no special raw materials required to implement the ISLP with the desired performance, weight, volume and power characteristics. Gallium Arsenide or other exotic materials and their associated increased manufacturing costs, low yield and availability delays can be avoided. Complementary Metal Oxide Semiconductor (CMOS) technology and its associated low manufacturing and raw materials costs can be utilized for ISLP manufacturing. Current manufacturing facilities and very large scale integration (VLSI) components can be utilized to manufacture a ISLP printed circuit boards or interface cards. Despite the need for parallel processing, high speed component interconnections and potentially Gigabytes of memory for implementation of an ISLP and associated QoS service functions at megabit per second rates, existing VLSI integrated circuits such as FPGAs can be used to produce prototype and mass produced units.

Custom VLSI implementation of the entire ISLP has a number of satellite resource utilization advantages in that the amount of required power, weight and volume for an ISL can be reduced. If custom VLSI implementation is the chosen manufacturing method, the initial cost of the first unit escalates substantially. Recurring costs, however, could possibly be decreased through the lower component count of custom VLSI manufacturing. Figure 9 is a representative FPGA based ISL prototype implementation which includes the entire ISL communications protocol stack, physical layer and all DLP processing (which is the transmission interface), and subsystem interface.

Weight, volume and power manufacturing DLP requirements dictate a final product that can be used on a TS21 satellite where weight, volume and power are at a premium. From a TS21 satellite point of view, the less weight, volume and power, the better. From a manufacturing point of view, the less weight, volume and power, the more difficult and expensive manufacturing can become. In the case of ISLP product manufacturing, a FPGA or custom VLSI manufacturing poses no new challenges or additional costs above and beyond current VLSI product manufacturing. Reduction in weight, volume and power through custom VLSI fabrication and manufacturing versus COTS FPGAs, poses no additional manufacturing requirements. Custom VLSI implementation can further reduce weight, volume and power consumption and possibly provide redundancy (currently not a TS21 ISL requirement) by allowing embedded or shared redundancy as opposed to dedicated hot standby (duplicate unit) redundancy.

Provided that a standard interface with adequate radar data rate capacity is utilized, the physical ISL to onboard subsystem interface poses no significant manufacturing cost or schedule requirements above those for ISL external satellite communication (transmission interface). Automated manufacturing and test equipment, as well as chip sets, already exists in numerous fabrication facilities for such standard interfaces.

The choice of HDLC with QoS service extensions for the only communications protocol above the physical layer greatly reduces the amount of risk associated with manufacturing of an ISL. For FPGA and custom VLSI hardware implementations, designs, hardware design language programs, FPGA cores, and test equipment and software already exist to implement the HDLC protocol. Only minor programming and test equipment modifications would be required to manufacture an extended HDLC protocol to include any desired QoS services.

5.5 ISL Communication Protocol Definition

In order for meaningful communication to take place, the information or data exchange procedures, syntax and format must be specified. Communication protocols define and specify the data exchange

procedures, syntax and format. Based on the previous discussion, including the five top level communications protocol requirements, the ISL communications protocol stack, or set of communication protocol functions, is defined as physical layer protocol with a data link layer protocol.

ISL communication occurs in two forms, external and internal to a satellite. External satellite ISL communication occurs via wireless, RF CDMA transmissions between an ISL subsystem on one TS21 satellite and another ISL subsystem on another TS21 satellite. Another possibility of this type is transmission between an ISL subsystem on a TS21 satellite and a ground station. Both are examples of the general case of an ISL subsystem communicating with an entity outside of the spacecraft on which the ISL subsystem resides. The second form of ISL communication is internal satellite communication where the ISL subsystem communicates with one or more other subsystems on the same satellite. This type of ISL internal satellite communication is usually via a physical connection such as a electrical or optical wires, cables, busses or LANs. In the case of external, wireless, RF, CDMA based communication, the physical layer communications protocol is specified via the chosen CDMA hardware components, a DS-CDMA protocol. In the case of internal communication, the physical, and possibly the data link and network layer protocols, are defined by the selected physical connection, such as a Myrinet LAN, IEEE 1553 or VME bus.

The DLP protocol is the only additional protocol that needs to be specified above and beyond physical link components. In both internal and external satellite ISL communication, the data link layer protocol, DLP, can be one and the same protocol. Having the same DLP protocol for both internal and external ISL communications yields performance, volume, weight, power and cost benefits.

Given the five top level requirements on the design and implementation of the ISLP, 1) Performance, 2) COTS Interoperability, 3) QoS functionality, 4) Interface and 5) Manufacturing, the ISLP is defined as an HDLC compliant data link protocol with extensions for improved performance and QoS services. A flexible and widely applicable protocol mechanism is defined, which is applied to an existing standard data link protocol (e.g., HDLC), to yield an ISLP that meets all requirements. The resulting TS21 ISLP is an international standard HDLC compliant and interoperable data link protocol that can be used for both internal and external satellite communications.

The protocol mechanism for increasing performance, adding data transport QoS functions and maintaining interoperability is applied to the HDLC protocol to define the new ISLP. The utilization of the HDLC compliant data link specifications, procedures [ISO13239], elements of procedures [ISO4335], frame formats, frame content [ISO3309] and services definitions [ISO8886], meets the interoperability requirement for a data link layer protocol. HDLC compliant data link protocols are the overwhelming majority (greater than 95%) of all data link protocols in use [ISO10171]. All QoS services, hence all performance modifications and extensions, are defined and selected using the existing HDLC standard I, U, S and XID frames [ISO3309, 4335, 8885, 10171]. The additional control bits are added to the existing Information field of the HDLC I-frame and to the Data User Sub-field of the XID-frame. The HDLC based ISLP, with its QoS extensions and resulting performance improvements, can meet the performance requirement of $\geq$ 100 Mbps radar data transmission. The new QoS functions implement an extended HDLC based ISLP that provides substantial performance improvement and needed QoS services, while providing interoperability with HDLC. Both the connectionless and connection oriented services and classes of HDLC procedures are defined as a part of the ISLP.

Three fundamental data transmission link components, which influence each other, can be identified: the application, the communication system, and the communication link. To overcome several performance bottlenecks, it is necessary that these components adapt to each other. This is partially already done, e.g., the communication system may adapt to the link load (rate control of Express Transfer Protocol - XTP, slow-start algorithm of TCP, etc.). ISLP QoS support enables the link and the communication system to adapt to the application requirements. The ISLP makes possible needed, innovative forms of adaptation that are not provided in existing data link or higher layer protocols:

1. The communication system can adapt to the application - composing a tailored protocol that includes only the functions required by a given application and type of packet.
2. The application can and should adapt to the communication link - The application should adapt to variable networking environments and should also adapt its data flow to the available bandwidth and the required quality of service.

The application of the protocol enhancement mechanism to extend the HDLC service set to include new QoS services and QoS parameters, allows for the adaptation of the application, the communication system, and the communication link into the optimum performance protocol services combination.

Although several directions have been proposed to solve the protocol related problems of adapting the application, the communication system, and the link: a) improvement of the existing protocol mechanisms, b) design of new protocols, c) the Application Level Framing [CT90] technique and d) a demultiplexed architecture, none of these techniques is interoperable with existing satellite or terrestrial link protocols, components and systems, violating one of the five main requirements and eliminating benefits of the ISLP design. The ISLP can be tailored as a custom protocol for each application and environment, but in an interoperable manner, thus providing the benefit of customization with the cost and schedule benefits of interoperability.

With the selection of the HDLC international standard data link protocol as the baseline specification and with extended services for QoS and performance, all requirements are met without the large costs and risks of violating interoperability. Through the use of the added QoS services, implemented with existing HDLC compliant procedures and frame format extensions, the application, communications system and the communication link can be adapted to one another. A set of QoS ISLP services optimized for the performance of the current combination of link and application(s) can be achieved. Performance is optimized through tailoring of the data link protocol to each unique user data and link performance combination. Each satellite implementation can therefore be an optimum combination of data link protocol services and implementations, while still adhering to a standard protocol. Not only can all the optimized ISLP implementations interoperate with the standard HDLC data link protocols in existing links, but all optimized, customized versions of the ISLP can interoperate with one another.

The new data link protocol specification is the goal of communications link designers and users - flexibility for performance and adaptation to each application, while retaining the advantages of standardization and interoperability. The cost savings of a standard and interoperability are retained while increased performance and tailored functionality are also provided. The remaining protocol specification effort becomes one of QoS service definition within the standard HDLC protocol.

5.5.1 QoS Services

A general and flexible model of QoS service provision (the protocol enhancement mechanism) is presented that does not restrict itself to any of the specific proposals for QoS service being discussed in various industry and standards bodies. At the ISLP level, it is technologically viable to incorporate mechanisms which can provide customer-specific QoS services even at very high speeds. Since the ability exists to implement the additional QoS functionality at high user data throughput rates, there is no need to restrict service offerings to simple schemes encoded in the existing TCP protocol type of service (ToS) bits.

Potential ISLP QoS functions and associated parameters, that meet link requirements while providing improved performance, include

1. Throughput or Bandwidth
   a) MTU Size
      Number of bits per data packet, requested by the application and set by link optimization. If link optimization sets a size different than an application requests, segmentation and reassembly functions must occur in the ISLP at packet sizes requested by the application.
   b) Number of Bits Per Second
      Number of b/s exchanged between service users, e.g., transactions per second

c) Rate
Quantity per unit of time in which consecutive data packets have to be delivered to the destination user, e.g., the rate of transmitting frames in the case of video traffic
d) Segmented Delivery
Whether segmented packet delivery is acceptable, in which case no segmentation or reassembly function is needed in the ISLP
e) Flow and Congestion Control
Specifying how data packets are routed, dropped, delayed and rerouted for space links with routers, switches and packet buffers, e.g., multiple satellite or terrestrial hop transmissions
f) Compression
Whether or not to use compression of data or headers, and choice of compression algorithms and compression ratio; involves a tradeoff between error rates and bandwidth

2. Time
a) Delay Limits
Acceptable elapsed time between sending a data packet from a service user until it is received by the destination service user
b) Response Time
Acceptable two-way delay and the processing time, typically needed for real-time control applications
c) Jitter
Acceptable rate variation in delay, response and other transmission time parameters
d) Interstream Synchronization
Amount of synchronization, if any, required between different data streams, lip sync between corresponding audio and video streams
e) Expedited Data
Delivery priorities

3. Reliability
a) Data Corruption Threshold
Quantity of data corruption accepted by the service user, e.g., percentage of corrupted data units within a data stream
b) Data Loss Threshold
Acceptable percentage of data packet loss
c) Replication of Data
Whether packet duplicates must be detected and or removed
d) Data Delivery Order
Whether the data packets must be delivered in the order of their transmission
e) Group Delivery
Multicast and broadcast - whether transmitted data have to be delivered to all members of the group, to at least one member, or to the majority of the group members
f. FEC
What type of error detection and correction algorithm or encoding to use including the selection of header only, header and body, Cyclic Redundancy Code (CRC) type and length, Reed-Solomon type and length, etc.
g) ARQ
Whether to use the standard Go-back-N or the extended services optional SR-ARQ with multiple buffers procedure

4. Security
a) Access Security
Whether identification before setting up a session is required
b) Data Security
What type of data protection to employ, e.g., Data Encryption Standard (DES), keys, length of encryption keys, etc.

c) Data Unit Manipulation
Management of single data packets can be specified in more detail, without considering their relation to other data packets within a data stream

By adding the ability to modify these new QoS parameters, the ISLP can be optimized for the combination of link characteristics and application (e.g., radar data) requirements. The additional QoS ISLP services are often viewed as transport protocol or higher layer protocol services. By adding these services as optional functions to the ISLP, even higher link performance can be obtained through the elimination of higher level protocols. This is the typical protocol stack arrangement used in real-time command and control applications for reducing time delays and improving throughput. The minimum protocol stack consists of a physical layer and a data link layer protocol with the user application interfacing to the data link layer protocol.

5.5.2 QoS Performance Functions

All QoS functions, including ARQ, FEC and MTU size functionality can be considered performance impacting functions. The QoS functions and other contributors to improved ISLP performance are:

1. Compression
2. Multiple buffer SR-ARQ
3. Adaptive FEC
4. Adaptive MTU
5. QoS service selection and implementation approach
6. Upper layer protocol implementation.

Each of these is now discussed further. The quantified analysis data of the performance contribution of each service is specified in Section 5.9: Performance.

5.5.2.1 Compression

Data compression can be defined as replacing a given bit pattern with an alternate bit pattern that requires fewer bits. As long as one knows the mapping of replaced bit patterns to compressed bit patterns, known as the compression algorithm, the original data bits can be recovered. Compression has been a very productive method for increasing data throughput using the familiar tradeoff of increased processing for decreased data transmission. A number of compression standards exist for voice, video, alphanumeric and graphical data. Experimental and non standard compression algorithms also exist. Whether or not TS21 radar data is compressible is not known as of this time. The ability to implement compression and change compression algorithms allow for the evolution of radar data compression. Compression ratios, original bit pattern to replacement pattern bit counts, exist in the ranges of 100 to 1 to 2 to 1. For ISLP utilization, both protocol control information and user data can be compressed. Compression inside the ISLP provides the most benefit when the user's data has not already been compressed before reaching the link protocol.

5.5.2.2 ARQ and FEC Coding Techniques

Most data link control (DLC) protocols (including the ISLP) fit into the following structure. The protocol operates between a transmitter and a receiver. A source feeds a sequence of messages into the transmitter. The transmitter adds some additional information to the messages and sends them over a communication channel to the receiver. The communication channel is unreliable and may occasionally lose or corrupt messages, though it cannot permute the order of messages (first-in-first-out - FIFO channel). There is also a reverse (similarly unreliable) channel that permits the receiver to send information back to the transmitter. The purpose of the DLC protocol is to permit the receiver to guarantee eventual delivery of all messages to the destination in the same order as generated by the source.

Coding techniques may be used to provide a more reliable communications system (reduce the probability of error), or to increase the efficiency (throughput) and lower the cost of a system (less power required), or both. The amount of improvement achieved when a coding scheme is used is referred to the coding gain for that scheme. The coding gain is determined by plotting the

probability of error versus E_b/N_o (signal energy per bit/ noise energy per Hertz) of both the non coded and coded transmissions, then measuring the difference in E_b/N_o required to achieve a given error rate. Although the use of coding schemes can produce impressive improvements, it should be noted that at sufficiently low values of E_b/N_o, (i.e., extreme channel interference or jamming) error correction coding actually my make the situation worse. This is common to all coding schemes. Thus under conditions of severe jamming, the use of error correction is not effective. The two most common methods utilized in communication systems for error detection and correction are ARQ and FEC.

ARQ typically adds a unique sequence number to the data blocks in a transmission which is incremented by one every time the transmitter sends a new message. The receiver acknowledges every single message. In practice, message sequence numbers can be reused (with care) and acknowledgments can be grouped together thereby not requiring a separate acknowledgment per message. The details of these performance improvement techniques are similar to existing DLC protocols and are not specified here. The transmitter has an accurate timer and that there exists a known time interval, T, which is larger than the round trip delay (of message and acknowledgment) across the channel. The duration of message transmission is referred to as a slot which is used as the unit of time. ARQ requires two way communications for sending acknowledgments of received messages and sending a request for retransmission for a data block that was never received, or contained errors that were not corrected by FEC.

FEC adds redundant bits at the transmitter to the data in the form of an error checking code which can detect and correct errors in data blocks or messages. FEC does not require two way communications, since the data is encoded prior to transmission and the receiver system decodes the data correcting the majority of errors which may occur. FEC works in conjunction with ARQ. If errors are detected that cannot be corrected, ARQ is used to request a retransmission of the data in error.

5.5.2.3 Multiple Buffer Selective Repeat ARQ

Most DLC protocols use one of two basic mechanisms to recover from messages lost due to errors: Go-back-N or Selective Repeat (SR) [S87b, BG87]. The basic idea of Go-back-N is that packets from A to B are numbered sequentially and this sequence number is sent in the header of the frame containing the packet. The Go-back-Number n, $n \geq 1$, is the parameter that determines how many packets are transmitted before an acknowledgment must be received. When an error is found in a packet or a packet is not acknowledged, N becomes the number of packets retransmitted, even though only one of these packets may have been received in error. The basic idea of SR-ARQ for data on a link from A to B is to accept out-of-order packets and to request retransmission from A only for those packets that are not correctly received. The main advantage of Go-back-N is that the implementation of the receiver is simple. There is very little state information to maintain and buffer management is accomplished through a single FIFO buffer. A large numbers of variations on the Go-back-N protocol have appeared in the literature [M78, TW79, T79]. The use of FIFO buffer at the receiver is of particular importance since it disassociates the speed of the receiver processing from the transmission rate of the channel. SR, while providing improved performance, is more complex to implement, particularly in terms of memory management at the receivers since packets may arrive, and will be accepted, in any order [S87b, AP86, RS89].

The standard HDLC protocol contains optional services for SR and multi-SR SR-ARQ retransmissions. For the ISLP, the HDLC standard S-frame format and syntax is used to perform SR-ARQ in accordance with the enhanced multi-SR option specified in the HDLC standard and Amendment 7 to the standard [ISO4335a7]. The ARQ improvement in the ISLP protocol comes through use of SR-ARQ, but mainly through the manner in which the SR-ARQ function is implemented.

The Multiple Buffer SR-ARQ concept is a simple two or three times replication of the Go-back-N hardware (e.g., having two or three FIFO buffers and associated state information). The advantage of Go-back-N ARQ, simple hardware implementation, is therefore maintained while providing the significant performance advantages of SR-ARQ. The Multiple Buffer SR-ARQ uses multiple replicated versions of a Go-back-N receiver in order to provide improved performance. The

receiver has one or more FIFO buffers. Associated with buffer i is a variable, IN(i) which represents the next message expected into that buffer. If no specific message is expected for that buffer (e.g., the buffer is empty) IN(i) is set to zero. The receiver consists of two portions that operate in an asynchronous fashion. The first portion (the write section) receives messages from the channel and loads them into one of the buffers. The second portion (the read section) reads messages from one of the buffer and delivers them to the destination. A Go-back-N implementation consists of a single buffer and the write section places an incoming (uncorrupted) message into this buffer only if the sequence number matches the variable IN. The SR-ARQ implementation is essentially an extension of the Go-back-N to multiple buffers, where the write section places an incoming message into the specific buffer whose IN(i) matches the sequence number. More specifically, upon receipt of a message n from the channel, the write section checks if any buffer has IN(i) = n. If so, it writes the message into the buffer. Otherwise, it checks if some buffer has IN(i) = 0 and if so, writes the message into that buffer. In either case, IN(i) is updated and an acknowledgment for message n is sent. If neither of the above options is possible, the message is discarded and no acknowledgment is sent. The operation of the read section is trivial. Essentially, it keeps track of the last message that it delivered to the destination. If a message with a sequence number one larger than this number appears as the first on any buffer, it reads that buffer and delivers this message. The transmitter operation is also quite simple. Whenever a message is transmitted, a copy is retained for possible retransmission until an acknowledgment is received. A message is scheduled for retransmission when T seconds have elapsed since its previous transmission. New messages received from the source are assigned a sequence number and transmitted only when there is no message awaiting retransmission. Thus, upon completion of a message transmission, the transmitter first checks if any retransmissions are scheduled. If not, it transmits the first new message. Otherwise, an old message is retransmitted which in general would be the message for which the maximum time (N slots) has elapsed since its previous transmission. There are circumstances in which the transmitter can know that the message will overflow before transmitting it. As a performance improvement, it can attempt to detect these situations and not transmit a message that is guaranteed to overflow (the example below would make this clear). This decision is based on the knowledge of the number of buffers at the receiver and the most recent N Acknowledgment/Negative Acknowledgment (ACK/NAK) messages it received. In many cases this is not possible either because the transmitter is not intelligent enough (implemented in hardware) or because the precise structure of the receiver (number of FIFO buffers) is not known to the transmitter. The correct operation of the protocol does not require the implementation of this performance improvement. By replicating the simplicity of the Go-back-N hardware two or three times, the performance of Multiple Buffer SR-ARQ approximates that of the ideal SR-ARQ.

5.5.2.4 Adaptive FEC

Adaptive FEC is the process of varying the amount of FEC redundant bits, or varying the method of calculating the FEC bits, or both, depending upon the link quality and user data needs. A change in the coding rate from 1/2 to 1/4 is an example of decreasing the amount of FEC bits in response to a higher quality (lower error rate) link or in response to a higher acceptable error rate by the user or application. Changing the FEC algorithm from a Reed-Solomon to a Golay code is an example of altering the method of calculating the FEC bits in response to link error characteristics or user data needs. ISLs differ from their terrestrial counterparts in error characteristics. Bit error rates (BERs) are typically lower on space links with adequate signal to noise ratios (SNR). Typical BERs for a ISLs are on the order of 10^{-7}, compared to 10^{-5} for terrestrial links. The pattern of errors are different in ISLs. ISL errors typically are the corruption of single bits here and there, as opposed to terrestrial links where errors tend to occur in bursts of several bits in a row. The goal of adaptive FEC is to use the optimum combination of the least number of FEC bits and the least complex coding algorithm to achieve the required error rate to meet user data needs. ISLs and terrestrial links require different types of FEC codes (algorithms) for optimum FEC of their different error characteristics.

In addition to link characteristics, application or user error tolerances span a wide range from accepting no errors to accepting the loss of millions of bits. Different user data require different BER QoS. For example, a video data transmission can tolerate the loss of entire packets with the result of a little snow in the received picture. For such video user data, the number of FEC bits can be reduced,

and perhaps eliminated all together, because the acceptable BER is quite high. Any space or terrestrial link has a variable BER, or link quality, due to a number of factors such as transmission medium conditions, thermal noise temperature of the receiver, E_b/N_o of the received signal, etc. The use of a FEC code that is designed for the worst case, to provide the lowest BER, results in the transmission of more FEC bits than are required for any given instant of link quality. Adapting the number of FEC bits and choosing a processing resource efficient code for an acceptable BER, will result in the transmission of a higher ratio of user data bits to overhead (i.e., FEC) bits and faster processing, yielding a higher user data throughput for the link.

The proposed ISLP contains the necessary user data BER QoS information to allow for decreasing (or increasing) the number of FEC bits based on the combination of link characteristics and user data requirements. Adapting the number and complexity of FEC bits to the user data needs can decrease the FEC overhead more than link quality adaptation alone. By constantly adjusting the number of FEC bits, through the selection of different codes or different rates of the same codes, based on user data and link quality parameters, a higher user data throughput is obtained.

5.5.2.5 Adaptive MTU

Adaptive MTU is defined as adapting the message transfer unit size to the link quality and QoS requirements of the transmitted data. Adaptive MTU can yield significant link throughput performance improvement. The concept can be viewed as taking the available transmission data rate and dividing this rate into segments called MTUs, frames, packets, messages, blocks, etc. ARQ, FEC, processing, segmentation and reassembly, QoS functions and other link related functions are then performed on the MTU size segments. The more segments (smaller MTU), the more times the link related functions must be executed. Conversely, the fewer segments (larger MTU), the fewer times the link related functions must be executed. ARQ and FEC functions are very sensitive to MTU size. The fewer segments - the larger the MTU - the better the performance of ARQ and FEC functions. However, the greater the bit error probability (or rate), p_b, the greater probability of an error in a MTU or frame and hence a greater number of retransmissions are required for larger MTU sizes. In addition, user data comes in predefined segment sizes. For example, voice data comes in small segments or packets with an MTU size of near 8 bytes or 32 bits, while video or file transfer data can come in MTU sizes of 65 thousand to millions of bits. The best performance is achieved through adapting the MTU size to a size between the optimum space or terrestrial link MTU size (based on bit error rates and propagation delay times) and user data MTU sizes.

TS21 ISLs differ from terrestrial link counterparts. The main characteristic of ISLs relevant to MTU sizing is the variable propagation delay times in comparison to the fixed terrestrial links. A TS21 constellation with inter-satellite spacing of 5000 km has a much different propagation delay time than a constellation with inter-satellite spacing of 10 m. This means that 500 times the number of data bits can be sent and can be in the link pipeline in the 5000 km case than in the 10 m case before any acknowledgment or indication of reception errors is received at the transmitter. In order to optimize link bandwidth and transmission rate capability, the link pipeline should be kept full of data. This can be accomplished one of two ways: transmit many small messages or transmit fewer, larger messages. Data link protocol functions such as time-out timers, retransmission schemes, error coding and message acknowledgments provide higher user data throughput with fewer, larger messages, as opposed to using more, smaller messages.

Application requirements, in conjunction with link delay characteristics, require that a data link protocol be flexible enough to accommodate a wide range of MTU sizes. The proposed ISLP adaptive MTU size mechanism is able to adapt the protocol operation to optimize user data throughput and link bandwidth utilization for both long and short delay links, while maintaining interoperability with other links using different MTU sizes. The ISLP MTU sizing mechanism can allow different links with different MTU sizes to interoperate without manual intervention required at any time before, during or after MTU size adjustments.

5.5.2.6 QoS Service Selection and Implementation

The combination of selected QoS functionality along with the link characteristics, e.g., SNR, error rates and error characteristics, affects data throughput in that the more QoS functions that are in use,

the more processing is required. Some QoS functions, however, improve data throughput performance. The effects of QoS selection will be determined by the implementation of the QoS functions. A fast, parallel processing hardware oriented implementation can reduce the effects of performing additional QoS functions to the point of not limiting performance. On the other hand, a poor software implementation can cause QoS selection and execution to become the link bottleneck, reducing data throughput to unacceptable levels.

5.5.2.7 Upper Layer Protocol Implementation

Upper layer protocol implementation greatly affects the overall data link throughput performance. This is true even though upper layer protocol performance is only loosely coupled to data link protocol operation. If upper layer protocols are going to be used over a satellite or terrestrial data link and if they are implemented in software, then optimization of upper layer protocols is a must for improved data throughput. The main optimization that needs to be performed is to reduce the number of memory accesses required for upper layer protocol processing.

5.6 ISLP Procedures

The ISLP procedures are the same as the HDLC procedures, specified in accordance with [ISO13239] and [ISO4335]. All ISLP extensions and associated parameters can be selected through the use of the existing HDLC procedures. Two new XID-frame responses to U-frames are required to be defined. One XID-frame is sent in response to the U-frame request for initiating ISLP extended HDLC operation. A second XID-frame is sent in response to the U-frame request for terminating ISLP extended HDLC operation. If ISLP operation is always in use, there is no need for these two new responses. However, should a mix of existing HDLC based and ISLP operations be required, the two new XID-frame responses are required.

The new service extensions to HDLC, turning the protocol into the ISLP, are therefore initiated in such a way as to be interoperable with existing HDLC U-frame compliant implementations and with the HDLC standard. New QoS and QoS inherent performance enhancing services are added using the existing procedures and frame structure of the HDLC standard.

5.7 ISLP Frame Formats

The ISLP frame formats are the same as the standard HDLC frame formats. Additional parameters are specified for three existing HDLC frames, the I-frame, U-frame, S-frame and XID-frame.

5.7.1 ISLP Information (I) Frame

The basic ISLP frame format is the same as the HDLC I-frame format, specified in accordance with [ISO3309]. Figure 11 illustrates the basic HDLC I-frame format.

Flag (F)	Address (A)	Control (C)	Information (I)	Frame Checking Sequencing (FCS)	Flag (F)
01111110	8 - 256 bits	32 bits Modulo 2^{32}	Variable # of bits	16 or 32 bits	01111110

Figure 11. The Basic HDLC I-Frame Format is the Basis for the ISLP I-Frame Format

The I-Frame fields are defined as follows.

1. Flag Field
   The flag field contains the flag bit sequence used for frame synchronization. All frames must start and stop with a flag field containing the same flag sequence. A single flag may be used as both the closing flag for one frame and the opening flag of another frame.
2. Address Field
   In command frames, the address field identifies the data station(s) for which the command is

intended. In response frames the address identifies the data station from which the response originated.

3. Control Field
   The control field indicates the type of command or responses and where appropriate, contains frame sequence numbers. The control field is used to convey a command to the addressed data station(s) to perform a particular operation or to convey a response to such a command from the addressed station.
4. Information Field
   The information field contains the user or application data. Any sequence of bits of any length or structure may be in the information field. This field in the I-frame contains the QoS selections and implementations.
5. Frame Checking Sequencing (FCS) Field
   This field contains a CRC error detection/correction FEC code for the frame bits after the opening flag and before the FCS field. Two lengths can be selected, a 16 or 32 bit CRC, with the longer FCS CRC code providing better FEC.

Additional QoS implementation bits are placed in the Information (I) or data field of the HDLC I-frame to accommodate the additional QoS service control data. Figure 12 illustrates the general frame structure of the ISLP with additional QoS bits.

Flag (F)	Address (A)	Control (C)	Information (I)		Frame Checking Sequencing (FCS)	Flag (F)
			Quality of Service (QoS) Selection & Implementation	User Data		
01111110	8 - 256 bits	32 bits	Variable # of bits	Variable # of bits	16 or 32 bits	01111110

QoS Selection & Implementation								
QoS Function Selection	Length to User Data	QoS Selected Function ID	QoS Selected Function Length	QoS Selected Function Implementation	• • •	QoS Selected Function ID	QoS Selected Function Length	QoS Selected Function Implementation
32 bits	32 bits	16 bits	32 bits	Variable # of bits		16 bits	32 bits	Variable # of bits

Figure 12. The General ISLP I-Frame Format with added QoS bits

The QoS selection and implementation fields are defined as follows.

1. QoS Function Selection Field
   The QoS Function Selection field uses one bit for each of the 21 defined QoS functions with 11 bits for future extensions. Each bit identifies whether the QoS function is included in the beginning of the Information field of the I-frame. Although the QoS Selected Function Identifier (ID) field is sufficient for identifying the QoS functions on an individual basis, by placing the list of selected functions in the front of the user data, header processing can be performed before buffering of the user data, greatly improving performance. In addition, an early allocation of resources can be made to further speed up QoS function and user data processing. Furthermore, should the receiver reject any of the selected QoS functionality due to insufficient resources, the XID frame to signal acceptance/denial of QoS services can be sent as early in the link negotiation process as possible. Table 4 depicts the QoS service to QoS Function Selection Bit mapping.

Table 4. QoS Function to Function Selection Bit Mapping

QoS FUNCTION TO FUNCTION SELECTION BIT MAPPING	
QoS Function	**QoS Function Selection Bit (set to a 1 if the function is selected)**
Throughput or Bandwidth	
1. Data packet (MTU) size	1
2. Number of bits per second	2
3. Rate (for consecutive packets)	3
4. Segmented delivery	4
5. Flow control/congestion control	5
6. Compression	6
Time	
7. Delay limits	7
8. Response time	8
9. Jitter	9
10. Interstream synchronization	10
11. Expedited data	11
Reliability	
12. Data corruption threshold	12
13. Data loss threshold	13
14. Replication of data	14
15. Data delivery order	15
16. Group delivery	16
17. Forward error correction (FEC)	17
18. Automatic repeat request (ARQ)	18
Security	
19. Access security	19
20. Data security	20
21. Data unit manipulation	21
22. Future Expansion	22 - 32

2. Length to User Data
   The Length to User field is used to specify how many bits of QoS information follow after the control field and before the user data in the Information field of the I-frame. This allows the parsing of header and user data information for immediate, separate and parallel processing and handling.
3. QoS Selected Function ID
   The QoS Selected Function ID field allows for the selection of the specific implementation of the QoS function chosen in the QoS Function Selection field. Within a QoS function, there can be many alternative implementations. For example, with the FEC function one can chose options such as block codes, convolutional codes, Reed-Solomon 1/4 codes, Reed-Solomon 1/2 codes, any number of custom encodings, etc. Since many options exist for implementing QoS functions, 16 bits are provided to allow for current and future specification of up to 2^{16} or 65,536 implementations and implementation variations.
4. QoS Selected Function Length
   The QoS Selected Function Length field provides the knowledge of how many bits are used to implement the QoS function. This field also provides the information of how many bits there are before the user data or the next QoS function in order to parse this field for immediate, separate and parallel processing from any other QoS information or user data. In

the case of FEC functions, knowing immediately the number of bits used for FEC can greatly speed up processing.

5. QoS Selected Function Implementation
This field contains the actual bits which are the results of performing the QoS function. It can contain decryption keys, FEC checksums and bits, the actual compression algorithm, etc.

Using the QoS bits within the added QoS fields at the beginning of the Information (I) field, an infinite number of extension implementations are possible. Figures illustrating some examples of the main performance enhancing QoS control bits within the ISLP frame structure are given below.

Flag (F)	Address (A)	Control (C)	Information (I)		Frame Checking Sequencing (FCS)	Flag (F)
			Quality of Service (QoS) Selection & Implementation	User Data		
01111110	8 - 256 bits	32 bits	Variable # of bits	Variable # of bits	16 or 32 bits	01111110

QoS Selection & Implementation					
QoS Function Selection FEC only	Length to User Data	FEC Function ID	FEC Function Length	FEC Function Implementation	User Data
32 bits	32 bits	16 bits	32 bits	Variable # of bits	Variable # of bits

Figure 13. ISLP I-Frame Format with added FEC QoS bits

Flag (F)	Address (A)	Control (C)	Information - Data (I)		Frame Checking Sequencing (FCS)	Flag (F)
			Quality of Service (QoS) Selection & Implementation			
01111110	8 - 256 bits	32 bits	Variable # of bits	Variable # of bits	16 or 32 bits	01111110

QoS Selection & Implementation								
QoS Function Selection MTU & FEC	Length to User Data	MTU Function ID	MTU Function Length	MTU Function Implementation	FEC Function ID	FEC Function Length	FEC Function Implementation	User Data
32 bits	32 bits	16 bits	32 bits	Variable # of bits	16 bits	32 bits	Variable # of bits	Variable # of bits

Figure 14. ISLP I-Frame Format with added MTU Sizing and FEC QoS bits

For FEC implementation, an identifier is required to select a FEC algorithm for QoS performance enhancing, extended functionality. The FEC function length field is required in order to specify the length of the FEC implementation field to be able to determine where the user data begins. The FEC Function Implementation Field is used to specify the bits used for FEC, and in the case of a convolutional algorithm, the location of FEC bits, and any other FEC parameters.

Rather than placing the QoS service extensions in the other types of HDLC frames (e.g., U-frame, S-frame or XID-frame), the I-frame is selected in order to keep all QoS functionality with the data for which the QoS functions apply. This has a number of advantages. The I-frames are self-defining. All necessary information to decode the frames and perform the extended QoS services are together in one place with the data on which the functions are to be performed. There is no storing of QoS parameters requiring a table look-up to match functionality with data. Any receiving satellite, ground station or subsystem can decode the data with minimal transmissions and storage of additional information. By not utilizing the mostly unconfirmed S, U or XID frames, error handling is reduced. No new responses to S, U or XID frames need be defined. By placing the QoS data at the beginning of the user data, header processing can be performed before buffering of the user data, greatly improving performance. An early allocation of resources can be made to further speed up QoS function and user data processing. Finally, should the receiver reject any of the selected QoS functionality due to insufficient resources, the XID frame to signal acceptance/denial of QoS services can be sent as early in the link negotiation process as possible.

5.7.2 ISLP Unnumbered Command Control (U) Frame

QoS extension of HDLC to initiate the ISLP protocol is performed using the existing HDLC standard U-frame content and format as specified within [ISO8885] and [ISO8885a9]. Figure 15 illustrates the HDLC U-Frame structure and content.

Flag (F)	Address (A)	Control (C)	Frame Checking Sequencing (FCS)	Flag (F)
01111110	8 - 256 bits	8 bits	16 or 32 bits	01111110

Control (C)							
1	1	M	M	P/F	M	M	M

Figure 15. The Basic HDLC Unnumbered Command Control U-Frame Format is the Basis for ISLP QoS Extension Selections

The U-Frame fields are defined as follows.

1. M bit
   These are the modifier function bits, used to select the command to be carried out by the receiving station(s). 15 of the possible 32 M bit combinations are defined in the HDLC standard as existing station commands with corresponding responses. Two of the remaining combinations are used to initiate and terminate the ISLP extended service operations.
2. P/F bit
   This is the poll bit, used by the primary station or combined station to solicit (poll) a response or sequence of responses from the secondary station(s) or combined station (1 = poll/final).

For selecting the ISLP protocol, extending the HDLC protocol for the ISLP defined QoS and inherent performance enhancing services, the five HDLC U-Frame M bits are set to a particular combination, chosen to be 01010, which does not correspond to any of the existing HDLC standard specified 15 command functions and 9 response functions. The resulting U-Frame initiating ISLP operation is depicted in Figure 16.

Flag (F)	Address (A)	Control (C)								Frame Checking Sequencing (FCS)	Flag (F)
01111110	8 - 256 bits	1	1	0	1	P/F	0	1	0	16 or 32 bits	01111110

Figure 16. The HDLC U-Frame bit Pattern initiating ISLP Operation

With five M bits, there are 2^5 or 32 optional extensions that could be specified. However, 15 of the 32 bit combinations are already used by the existing HDLC standard. Since for the ISLP there are 21 QoS extensions defined, there are not enough remaining M bit combinations to specify the QoS selections. In order to maintain interoperability with the existing HLDC Frame formats and contents, the U-frame cannot be used to specify the exact QoS selection. Instead, QoS function selection and optional implementations are performed in the Information field of the HDLC I-frame. Allowing for future expansion of an additional 11 QoS functions, 32 bits are set aside in the I-frame information field to select the desired QoS functionality. The 32 bits of the QoS Function Selection field in Figure 12 provide for the selection of the desired QoS functions.

For terminating the ISLP protocol operation, returning to non extended HDLC protocol operation, the five HDLC U-Frame M bits are set to another particular combination, chosen to be 10101, which does not correspond to any of the existing HDLC standard specified 15 command functions and 9 response functions. The resulting U-Frame terminating ISLP operation is depicted in Figure 17.

Flag (F)	Address (A)	Control (C)								Frame Checking Sequencing (FCS)	Flag (F)
01111110	8 - 256 bits	1	1	1	0	P/F	1	0	1	16 or 32 bits	01111110

Figure 17. The HDLC U-Frame bit Pattern terminating ISLP Operation

The HDLC U-frame is used to provide additional data link control functions and unnumbered information transfer. The U-frame is intended to extend the number of data link control functions. The U-frame optional information field can be used to send information such as status, application data, operation, interruption, temporal data, link layer programs or parameters to another link node over a communications link. However, reception of the U-frame is not sequence number verified by the existing HDLC link procedures. A U-frame may therefore get lost or duplicated. In addition, there is no specified response to the U-frame information. Because U-frames are unacknowledged and unnumbered, they are chosen to only convey the ISLP option, to convey that QoS extensions are desired. QoS specifications and function IDs are not transmitted via the unreliable U-Frame. Should a mix of existing HDLC based and ISLP data link protocol operations be required, two new XID-frame responses to ISLP U-frames are required. One XID-frame is sent in response to the U-frame request for initiating ISLP extended HDLC operation. A second XID-frame is sent in response to the U-frame request for terminating ISLP extended HDLC operation. If ISLP operation is always in use, there is no need for these two new responses. Initiation and termination of ISLP

extensions of the HDLC data link protocol are therefore accomplished via existing HDLC U-frames and procedures, assuring interoperability with existing HDLC U-frame compliant implementations and with the HDLC standard.

5.7.3 ISLP Supervisory (S) Frame

The HDLC S-frame is used to enter and convey the SR-ARQ options of the standard HDLC protocol. A multi-SR option is available allowing for the retransmission of non consecutive frames [ISO4335a7]. The new ISLP makes use of the existing HDLC S-frame to perform SR-ARQ. Figure 18 illustrates the S-Frame structure and content.

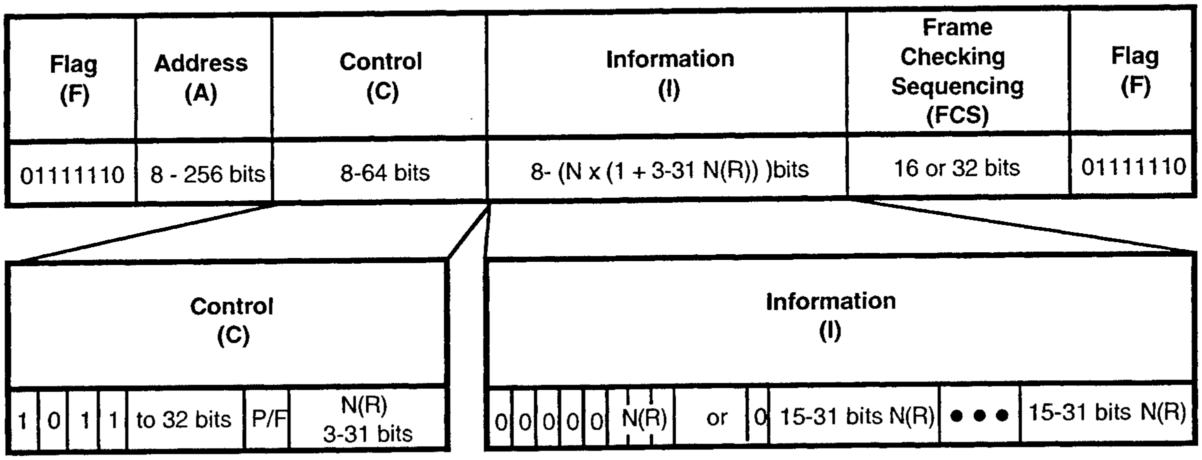

Figure 18. The Basic HDLC Supervisory S-Frame Format is the Basis for ISLP SR-ARQ

The S-Frame fields are defined as follows.

1. N(R) bits
   These are the sequence numbers of the frames to be retransmitted. For multi-SR, any number of non sequential frame numbers can be placed in the information field. The length of the N(R) field depends upon the maximum allowable number of outstanding messages ranging from 8 (3 bits) to 2,147,483,768 (31 bits).
2. P/F bit
   This is the poll bit, used by the primary station or combined station to solicit (poll) a response or sequence of responses from the secondary station(s) or combined station (1 = poll/final).

For selecting the SR-ARQ options, the first four bits of the control field are always set to 1011.

5.7.4 ISLP Exchange Information (XID) Frame

The XID-frame is used in the existing HDLC standard to exchange data link information between two or more stations. The information exchanged includes "any and all essential operating characteristics such as identification, authentication, and selection of optional functions and facilities concerning each station." "Mechanisms are provided to permit the general purpose XID-frame information field to be used to negotiate private parameters in a single XID exchange simultaneously with negotiation of the defined basic parameters" [ISO8885].

Confirmation and communication of QoS selections are performed using the existing HDLC standard XID-frame content and format as specified within [ISO8885, ISO8885a9]. Figure 19 illustrates the standard XID frame structure and content.

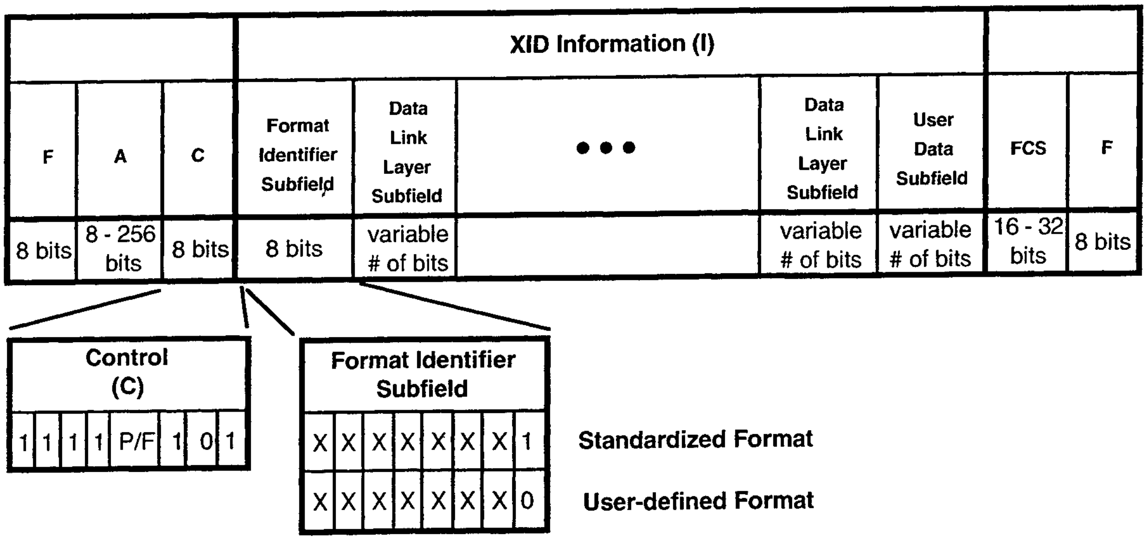

Figure 19. The Basic HDLC XID Frame Structure and Content is the Basis for ISLP QoS Extension Selections

As a part of the ISLP U-frame operation, two new XID-frame responses to acknowledge the new ISLP U-frames are required. One XID-frame is sent in response to the U-frame request for initiating ISLP extended HDLC operation. A second XID-frame is sent in response to the U-frame request for terminating ISLP extended HDLC operation. Again, if ISLP operation is always in use, there is no need for these two new responses. The new ISLP protocol is therefore initiated in such a way as to be interoperable with existing HDLC U-frame compliant implementations and with the HDLC standard. The XID-frame can also be used to communicate the current QoS selections. The HDLC compliant XID-frame used to confirm ISLP initiation and I-frame QoS selections is illustrated in Figure 20.

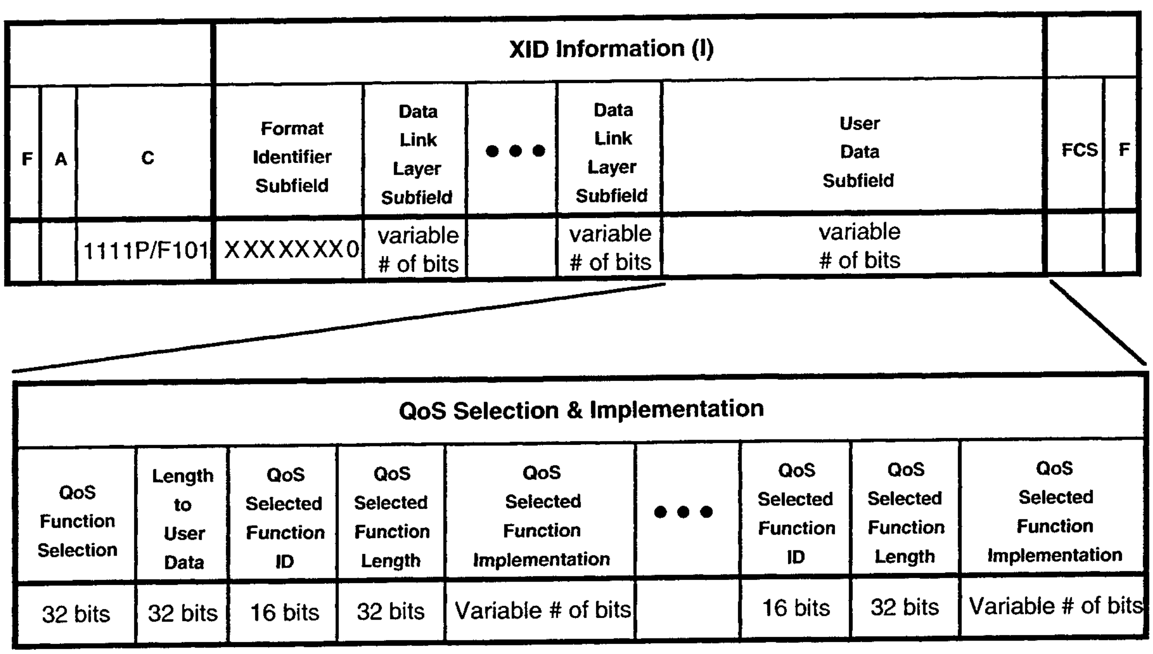

Figure 20. The ISLP XID Frame confirms QoS Operation initiation with an HDLC compliant XID Frame

The HDLC compliant XID-frame used to confirm U-frame termination is illustrated in Figure 21.

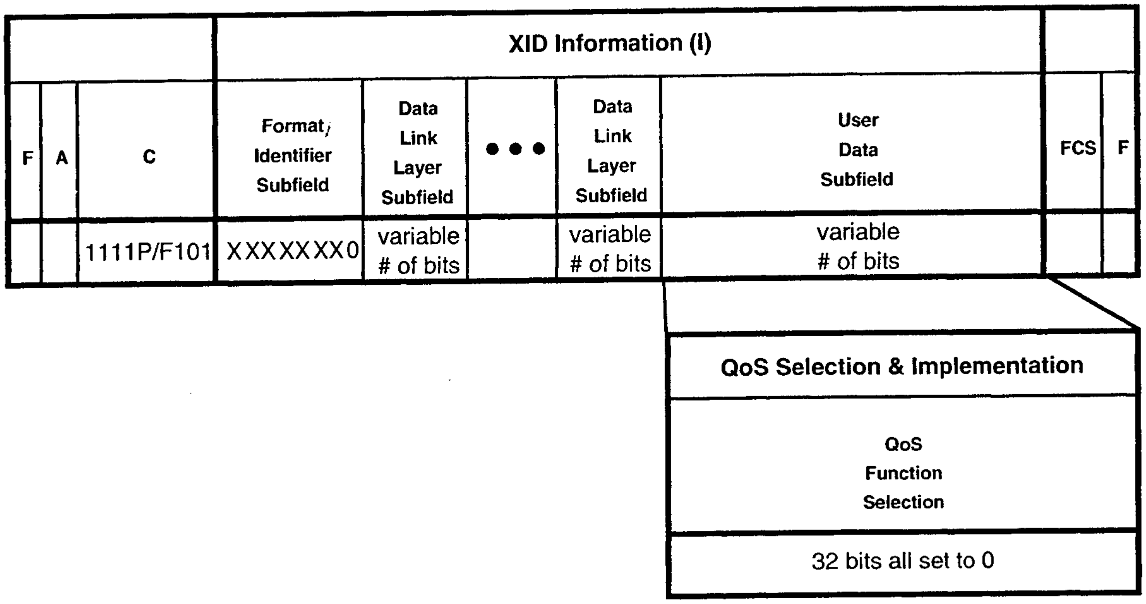

Figure 21. The ISLP XID Frame confirms QoS Operation termination with an HDLC compliant XID Frame

Together with the I-frames and U-frames, the new XID-frames implement an extended ISLP that is interoperable with HDLC, provides additional services and additional performance. The existing HDLC standard service interfaces and frame formats can support the new data link services.

5.8 Interface Definition

With the use of an extended HDLC as the ISLP, interfaces can follow the ISO OSI reference model [ISO7498] standards for interfacing between the data link protocol layer services [ISO8886] and: physical protocol layer [ISO10022], network layer protocols (e.g., IP) [ISO8348], transport layer protocols (e.g., TCP/UDP) [ISO8072], or the user application itself [ISO9545]. The existing ISO international standard service interfaces support the new data link services.

In addition, two de-facto commercial standard interfaces and interface development environments are also supported by the new ISLP. The Network Device Interface Specification (NDIS) and the Open Data-Link Interface (ODI) are compatible with ISLP and are used to provide Internet protocol stack interoperability. Figure 22 illustrates the relationship between the ISLP and the NDIS and ODI de-facto interface standards.

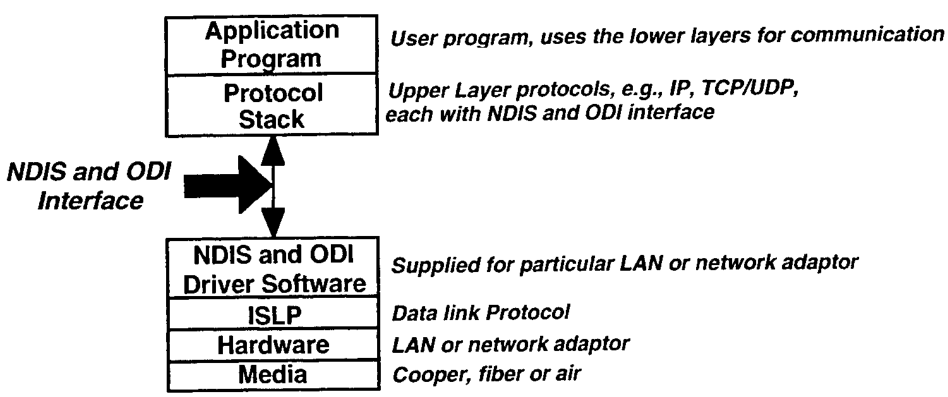

Figure 22. The ISLP is compatible with NDIS and ODI Interfaces

5.9 Performance

Performance improvement is achieved through the addition of performance enhancing QoS services, the optional elimination or encapsulation of upper layer protocols, and a parallel processing and VLSI (e.g., FPGA) hardware implementation. Performance enhancing QoS services and associated functions are in previous sections and include: variable compression, multiple buffer SR-ARQ, adaptive FEC algorithms and procedures, and dynamic and adaptive MTU or data packet sizing. The elimination or encapsulation of additional upper layer protocols through the use of the newly defined additional data link services provide another large performance benefit. The performance improvement of the key performance enhancing QoS services of compression, multiple buffer SR-ARQ, adaptive FEC and adaptive MTU, QoS selection/implementation and upper layer protocols removal/encapsulation/implementation is now quantified in the following sections.

5.9.1 Performance Quantification

In order to remove most variables and resulting validity restrictions from performance determinations, the link bit error rate and link utilization percentage are used as the performance metrics. This evaluation matrix, link utilization versus link bit error rate, yields the maximum useable results and makes use of the best existing data. Link utilization, when multiplied times the link transmission capacity, yields an independent determination of link data throughout rates and thereby provides the most often sought after performance data. As a group, the following sections provide a detailed quantification of the ISLP performance versus existing link implementation options.

5.9.1.1 Compression

For satellite or terrestrial data link protocol utilization, both protocol control information and user data can be compressed. Compression can achieve a range of 10000% to 2% data throughput performance increase. Lossless data compression algorithms on the order of 100 to 1 compression have been demonstrated for video and other types of data. A 100 to 1 compression would increase data throughput by 10000%, or a factor of 100. The worst case benefit of a 2% increase in throughput would occur if the data were already compressed and only the protocol header could be compressed along with minimal compression of already compressed user data. Obviously, compression provides the most benefit when the user's data has not already been compressed before reaching the link protocol. Since the data to be transmitted over the link varies in the amount of compression possible and varies in whether or not it has already undergone compression, an average amount of compression can be assumed. Given the ability to specify a wide range of custom and standard compression algorithms using the ISLP QoS fields, a conservative average compression of 2 to 1 is assumed. Compression is therefore estimated to provide a 50% improvement in link throughput.

5.9.1.2 Multiple Buffer Selective Repeat ARQ

Multiple Buffer SR-ARQ can achieve a range of more than 100% to 2.5% data throughput performance increase. The maximum throughput improvement with Multiple Buffer SR ARQ over Go-back-N ARQ varies with a number of factors, mainly the link error rate (or probability of error), transmission rate, overhead percentage (ratio of data bits to control, i.e., protocol and FEC, bits), and MTU (packet) length. Using the link performance formulas validated by operational use and depicted in Equations 1 and 2, Table 5 summarizes the performance improvement achievable with SR-ARQ under various link conditions.

$$\frac{\mathbf{D}}{\mathbf{C}} = \left(\frac{l}{l + l'}\right)\left[\frac{1 - p}{1 + (a - 1)p}\right] \leq 1 \qquad (1)$$

Equation 1. Go-Back-N Normalized Data Rate Formula [S87a]

$$\frac{\mathbf{D}}{\mathbf{C}} = \frac{(1-p)l}{(l+l')} \leq 1 \qquad (2)$$

Equation 2. SR-ARQ Normalized Data Rate Formula [S87a]

D = average data rate in bits/sec delivered to the receiving station in bits/sec
C = link transmission rate in bits/sec
D/C = normalized data rate, link efficiency
l' = length of the packet or message control (protocol overhead) fields/information in bits
l = length of the packet or message data field or user information in bits
p = the packet or message error probability = $1 - (1 - p_b)^{l+l'}$
a = parameter relating throughput to packet, ratio of time between frames to frame transmission time
= $1 + t_{out} / t_I = t_T/t_I$, $a \geq 1$

Table 5a. SR-ARQ vs. Go-Back-N ARQ Link Performance for 5000 KM Link Conditions

GO-BACK-N AND SR-ARQ LINK PERFORMANCE With 5000 Kilometer Maximum TS21 Satellite Separation												
Link Parameters										**Go-Back-N ARQ**	**SR ARQ**	**SR Gain**
p_b	l'	l	p	t_{out}	t_I	t_p	t_{proc}	TX rate	a	D/C	D/C	%
bits	bits	bits	bits	sec	sec	sec	sec	b/s				%
10^{-3}	136	307	3.58E-01	0.0343	4.43E-06	1.67E-02	0.001	10^8	7753	0.0002	0.4449	277556[1]
10^{-3}	136	4000	9.84E-01	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.0000	0.0154	81883
10^{-4}	136	1101	1.16E-01	0.0344	1.24E-05	1.67E-02	0.001	10^8	2779	0.0024	0.7865	32320
10^{-4}	136	4000	3.39E-01	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.0023	0.6395	28188
10^{-5}	136	3621	3.69E-02	0.0344	3.76E-05	1.67E-02	0.001	10^8	917	0.0267	0.9283	3377
10^{-5}	136	4000	4.05E-02	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.0267	0.9279	3371
10^{-6}	136	11595	1.17E-02	0.0346	1.17E-04	1.67E-02	0.001	10^8	296	0.2202	0.9769	343.66
10^{-6}	136	4000	4.13E-03	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.2172	0.9631	343.45
10^{-7}	136	36811	3.69E-03	0.0351	3.69E-04	1.67E-02	0.001	10^8	96	0.7353	0.9926	35.01
10^{-7}	136	4000	4.14E-04	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.7192	0.9667	34.41
10^{-8}	136	116552	1.17E-03	0.0367	1.17E-03	1.67E-02	0.001	10^8	32	0.9624	0.9977	3.66
10^{-8}	136	4000	4.14E-05	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.9349	0.9671	3.44
10^{-9}	136	368714	3.69E-04	0.0417	3.69E-03	1.67E-02	0.001	10^8	12	0.9951	0.9993	0.42
10^{-9}	136	4000	4.14E-06	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.9638	0.9671	0.34
10^{-10}	136	1166123	1.17E-04	0.0577	1.17E-02	1.67E-02	0.001	10^8	6	0.9992	0.9998	0.058
10^{-10}	136	4000	4.14E-07	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.9668	0.9671	0.034
10^{-11}	136	3687750	3.69E-05	0.1081	3.69E-02	1.67E-02	0.001	10^8	4	0.9998	0.9999	0.011
10^{-11}	136	4000	4.14E-08	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.9671	0.9671	0.0034
10^{-12}	136	11661965	1.17E-05	0.2676	1.17E-01	1.67E-02	0.001	10^8	3	0.9999	1.0000	0.0027
10^{-12}	136	4000	4.14E-09	0.0344	4.14E-05	1.67E-02	0.001	10^8	833	0.9671	0.9671	0.0003

[1] At a link bit error rate of 10^{-3}, Go-Back-N achieves virtually no throughput while SR-ARQ achieves a throughput near 45% in which case the throughput improvement of SR-ARQ over Go-Back-N can be viewed as the difference between SR and Go-Back-N divided by Go-Back-N as opposed to simply the difference between SR and Go-Back-N. The improvement can also be viewed as infinite, an operational link vs. having a non operational link.

Table 5b. SR-ARQ vs. Go-Back-N ARQ Link Performance for 10 Meter Link Conditions

GO-BACK-N AND SR-ARQ LINK PERFORMANCE With 10 Meter Minimum TS21 Satellite Separation												
Link Parameters										Go-Back-N ARQ	SR ARQ	SR Gain
p_b	l'	l	p	t_{out}	t_I	t_p	t_{proc}	TX rate	a	D/C	D/C	%
bits	bits	bits	bits	sec	sec	sec	sec	b/s				%
10^{-3}	136	307	3.58E-01	0.0010	4.43E-06	3.33E-08	0.001	10^8	229	0.0054	0.4449	8154[1]
10^{-3}	136	4000	9.84E-01	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.0006	0.0154	2576
10^{-4}	136	1101	1.16E-01	0.0010	1.24E-05	3.33E-08	0.001	10^8	84	0.0739	0.7865	964
10^{-4}	136	4000	3.39E-01	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.0648	0.6395	887
10^{-5}	136	3621	3.69E-02	0.0011	3.76E-05	3.33E-08	0.001	10^8	30	0.4517	0.9283	106
10^{-5}	136	4000	4.05E-02	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.4503	0.9279	106
10^{-6}	136	11595	1.17E-02	0.0012	1.17E-04	3.33E-08	0.001	10^8	12	0.8701	0.9769	12.27
10^{-6}	136	4000	4.13E-03	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.8692	0.9631	10.81
10^{-7}	136	36811	3.69E-03	0.0017	3.69E-04	3.33E-08	0.001	10^8	6	0.9757	0.9926	1.74
10^{-7}	136	4000	4.14E-04	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.9564	0.9667	1.08
10^{-8}	136	116552	1.17E-03	0.0033	1.17E-03	3.33E-08	0.001	10^8	4	0.9944	0.9977	0.33
10^{-8}	136	4000	4.14E-05	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.9660	0.9671	0.11
10^{-9}	136	368714	3.69E-04	0.0084	3.69E-03	3.33E-08	0.001	10^8	3	0.9984	0.9993	0.08
10^{-9}	136	4000	4.14E-06	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.9670	0.9671	0.01
10^{-10}	136	1166123	1.17E-04	0.0243	1.17E-02	3.33E-08	0.001	10^8	3	0.9995	0.9998	0.024
10^{-10}	136	4000	4.14E-07	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.9671	0.9671	0.001
10^{-11}	136	3687750	3.69E-05	0.0748	3.69E-02	3.33E-08	0.001	10^8	3	0.9999	0.9999	0.007
10^{-11}	136	4000	4.14E-08	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.9671	0.9671	0.0001
10^{-12}	136	11661965	1.17E-05	0.2342	1.17E-01	3.33E-08	0.001	10^8	3	1.0000	1.0000	0.0023
10^{-12}	136	4000	4.14E-09	0.0011	4.14E-05	3.33E-08	0.001	10^8	27	0.9671	0.9671	0.0000

[1] At a link bit error rate of 10^{-3}, Go-Back-N achieves virtually no throughput while SR-ARQ achieves a throughput near 45% in which case the throughput improvement of SR-ARQ over Go-Back-N can be viewed as the difference between SR and Go-Back-N divided by Go-Back-N as opposed to simply the difference between SR and Go-Back-N. The improvement can also be viewed as infinite, an operational link vs. having a non operational link.

Table 5c. SR-ARQ vs. Go-Back-N ARQ Link Performance for 600 KM Link Conditions

GO-BACK-N AND SR-ARQ LINK PERFORMANCE With 600 Kilometer Satellite-Ground Down-Link Operation												
Link Parameters										Go-Back-N ARQ	SR ARQ	SR Gain
p_b	l'	l	p	t_{out}	t_I	t_p	t_{proc}	TX rate	a	D/C	D/C	%
bits	bits	bits	bits	sec	sec	sec	sec	b/s				%
10^{-3}	136	307	3.58E-01	0.0050	4.43E-06	2.00E-03	0.001	10^8	1132	0.0011	0.4449	40482[1]
10^{-3}	136	4000	9.84E-01	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.0001	0.0154	12093
10^{-4}	136	1101	1.16E-01	0.0050	1.24E-05	2.00E-03	0.001	10^8	407	0.0163	0.7865	4727
10^{-4}	136	4000	3.39E-01	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.0150	0.6395	4163
10^{-5}	136	3621	3.69E-02	0.0051	3.76E-05	2.00E-03	0.001	10^8	136	0.1552	0.9283	498
10^{-5}	136	4000	4.05E-02	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.1552	0.9279	498
10^{-6}	136	11595	1.17E-02	0.0052	1.17E-04	2.00E-03	0.001	10^8	46	0.6425	0.9769	52.04
10^{-6}	136	4000	4.13E-03	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.6390	0.9631	50.72
10^{-7}	136	36811	3.69E-03	0.0057	3.69E-04	2.00E-03	0.001	10^8	17	0.9389	0.9926	5.73
10^{-7}	136	4000	4.14E-04	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.9200	0.9667	5.08
10^{-8}	136	116552	1.17E-03	0.0073	1.17E-03	2.00E-03	0.001	10^8	7	0.9904	0.9977	0.73
10^{-8}	136	4000	4.14E-05	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.9622	0.9671	0.51
10^{-9}	136	368714	3.69E-04	0.0124	3.69E-03	2.00E-03	0.001	10^8	4	0.9980	0.9993	0.12
10^{-9}	136	4000	4.14E-06	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.9666	0.9671	0.05
10^{-10}	136	1166123	1.17E-04	0.0283	1.17E-02	2.00E-03	0.001	10^8	3	0.9995	0.9998	0.028
10^{-10}	136	4000	4.14E-07	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.9671	0.9671	0.005
10^{-11}	136	3687750	3.69E-05	0.0788	3.69E-02	2.00E-03	0.001	10^8	3	0.9998	0.9999	0.008
10^{-11}	136	4000	4.14E-08	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.9671	0.9671	0.0005
10^{-12}	136	11661965	1.17E-05	0.2382	1.17E-01	2.00E-03	0.001	10^8	3	1.0000	1.0000	0.0024
10^{-12}	136	4000	4.14E-09	0.0051	4.14E-05	2.00E-03	0.001	10^8	124	0.9671	0.9671	0.0001

[1] At a link bit error rate of 10^{-3}, Go-Back-N achieves virtually no throughput while SR-ARQ achieves a throughput near 45% in which case the throughput improvement of SR-ARQ over Go-Back-N can be viewed as the difference between SR and Go-Back-N divided by Go-Back-N as opposed to simply the difference between SR and Go-Back-N. The improvement can also be viewed as infinite, an operational link vs. having a non operational link.

D = average data rate in bits/sec delivered to the receiving station in bits/sec
C = link transmission rate in bits/sec
D/C = normalized data rate, link efficiency
l' = length of the packet or message control (protocol overhead) fields/information in bits
l = length of the packet or message data field or user information in bits
p = the packet or message error probability = $1 - (1 - p_b)^{l+l'}$
a = parameter relating throughput to packet, ratio of time between frames to frame transmission time
= $1 + t_{out} / t_I = t_T/t_I$, $a \geq 1$
p_b = the bit error probability of the link
t_{out} = timeout interval, at the end of which an acknowledgment arrives = $2t_p + 2t_I + t_{proc}$
t_I = time to transmit a message -MTU or packet (data + overhead or control).
$t_T = t_I + t_{out}$ = minimum time between successive packets or messages
t_p = propagation delay time = speed of light/distance = 3×10^8 m/s divided by distance in meters
= 0.0167 sec for 5000 km and 3.33×10^{-8} sec for 10 m (TS21 satellite constellation ranges)
t_{proc} = packet or message processing delay
TX = transmission rate in TS21 radar payload data bits per second.

Figure 23 depicts the performance improvement available when using SR-ARQ instead of Go-Back-N ARQ with the optimum link MTU size (defined in section 5.9.1.4).

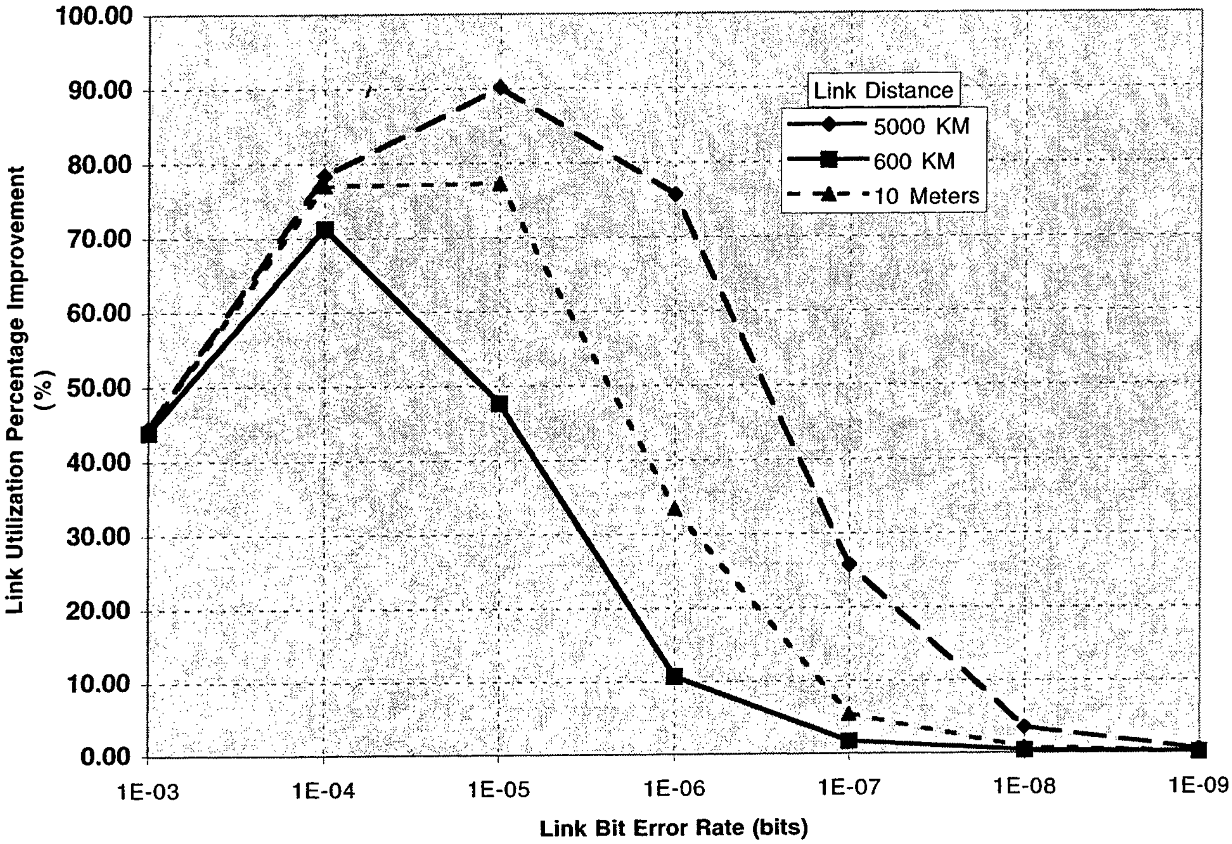

Figure 23. SR vs. Go-Back-N ARQ Improvement in Link Utilization

If the ISL probability of error is in the range of 10^{-3} and 10^{-7}, then Multiple Buffer SR-ARQ can achieve a greater than 100% increase (or doubling) in link throughput. Assuming that a typical link spends 50% of the time at 10^{-7}, 15% of the time at 10^{-6} and 10^{-8}, 7.5% of the time at 10^{-5} and 10^{-4}, and spends 5% of the time operating at a bit error rate of 10^{-3}, using a 100% improvement for 10^{-3}, 10^{-4}, and 10^{-5}, and a link distance of 600 km, then a 31% improvement in data throughput is expected through the use of the SR-ARQ QoS.

5.9.1.3 Adaptive FEC

Adapting the FEC amount of bits and type of encoding algorithm to the link quality increases the link throughput about 7% based on COMSAT experience in their CLA-2000™ satellite link product [CSAT98]. Adapting the number of FEC bits to the user data needs can decrease the FEC overhead to user data ratio even more than pure link quality adaptation. If one assumes a worst case of 50% FEC bits, (e.g., a rate 1/2 code), then the maximum achievable gain is 50% resulting from the elimination of all FEC bits in cases such as uncompressed radar data transmission where errors in the transmission are allowed. The reduction in processing delays achieved through the reduction or elimination of FEC processing can also add additional user data throughput improvement. If the link transmission rate can be increased in cases where the processing delays from FEC are reduced, an additional link throughput improvement in proportion to the processing reduction can be achieved. For example, if FEC processing accounts for 25% of the processing time in the satellite, then the complete elimination of FEC processing could achieve an additional throughput of 25%, above the maximum of 50% achievable by not transmitting the FEC bits. If FEC functionality is performed in

parallel with other data link or higher layer protocol functions, no processing gains and hence no data throughput gains would be realized through the elimination of FEC processing. Adaptive FEC is therefore able to increase link performance by a maximum of 50% and a minimum of 7%. For purposes of this analysis, the minimum of 7% is assumed as the expected performance gain resulting from adaptive FEC QoS functionality.

5.9.1.4 Adaptive MTU

In general, the fewer segments - the larger the MTU - the better the performance of SR-ARQ and FEC functions. Since user data comes in predefined segment sizes, the best performance is achieved through compromise between as large as possible an ISLP MTU size and user data MTU sizes. For satellite transmission, the optimum MTU size can be approximated using the formula depicted in Equation 3.

$$l_{\text{opt}} = \frac{l'}{2}\left[\sqrt{1 - \frac{4}{l' \log_e(1-p_b)}} - 1\right] \qquad (3)$$

Equation 3. Optimum MTU Size Approximation Formula [S87a]

The following table depicts the ranges of optimum MTU sizes using the formula in Equation 3, the minimum number of control bits, l', for the new ISLP and a variety of link conditions, including standard and new ISLP link protocol combinations.

Table 6. Calculated Optimum MTU Sizes

OPTIMUM MTU (PACKET) LENGTHS FOR VARIOUS LINK COMBINATIONS											
Link Characteristics		Link Bit Error Probability, p_b									
	l'	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
Standard HDLC with HDLC only	72	235	814	2648	8450	26797	84817	2.7E+5	8.5E+5	2.7E+6	8.5E+6
HDLC based ISLP with ISLP only	136	307	1101	3621	11595	36811	1.2E+5	3.7E+5	1.2E+6	3.7E+6	1.2E+7
Standard HDLC with IPv4, UDP	392	460	1794	6069	19604	62415	2.0E+5	6.3E+5	2.0E+6	6.3E+6	2.0E+7
Standard HDLC with IPv4, TCP	456	485	1920	6529	21128	67301	2.1E+5	6.8E+5	2.1E+6	6.8E+6	2.1E+7
HDLC based ISLP with IPv4, UDP	456	485	1920	6529	21128	67301	2.1E+5	6.8E+5	2.1E+6	6.8E+6	2.1E+7
HDLC based ISLP with IPv4, TCP	520	507	2036	6956	22545	71852	2.3E+5	7.2E+5	2.3E+6	7.2E+6	2.3E+7
HDLC based ISLP with ISLP only and typical QoS options (est.[3])	592	529	2155	7404	24037	76647	2.4E+5	7.7E+5	2.4E+6	7.7E+6	2.4E+7
HDLC based ISLP with IPv4, UDP and typical QoS options (est.[2])	922	604	2611	9153	29907	95561	3.0E+5	9.6E+5	3.0E+6	9.6E+6	3.0E+7
HDLC based ISLP with IPv4, TCP and max. QoS options (est.[1])	1760	712	3407	12416	41082	1.3E+5	4.2E+5	1.3E+6	4.2E+6	1.3E+7	4.2E+7

[1] 21 QoS functions = 21 x (16 function ID + 32 function length bits + avg. of 8 function implementation bits) + 32 bits function selection bits + 32 length to user data bits + 520 bits

[2] Compression, response time, data loss threshold, data delivery order, FEC, ARQ, and data security = 7 x (16 function ID + 32 function length bits + avg. of 8 function implementation bits) + 32 bits function selection bits + 32 length to user data bits + 456 (HDLC, IP and UDP) bits

[3] Compression, response time, data loss threshold, data delivery order, FEC, ARQ, and data security = 7 x (16 function ID + 32 function length bits + avg. of 8 function implementation bits) + 32 bits function selection bits + 32 length to user data bits + 136 (HDLC) bits

In order to calculate the performance improvement with adaptive MTU, Table 5c and Table 6 (using formulas in Equations 1, 2 and 3) are combined into Table 7. Use of Table 5c data implies that the MTU gains in Table 7 are for an ISL distance of 600 km. Combining Tables 5a and 5b with Table 6

would yield the MTU gains for the extreme ranges of the ISL, 5000 km and 10 m. 600 km is chosen as the representative distance for the TS21 ISL. A non adaptive MTU or message size of 4,000 bits (500 bytes), is typical of terrestrial link MTU sizes and was therefore chosen as the default non adaptive, fixed MTU size.

Table 7. Adaptive MTU Performance Improvement

ADAPTIVE MTU SIZING PERFORMANCE GAINS AT 600 KM DISTANCE									
Link Parameters and ARQ Mechanism								MTU Optimization Gains	
p_b bits	l' bits	l optimum bits	Go-Back-N D/C	Selective Repeat D/C	l fixed bits	Go-Back-N D/C	Selective Repeat D/C	Go-Back-N D/C %	Selective Repeat D/C %
10^{-3}	136	307	0.0011	0.4449	4000	0.0001	0.0154	1000	42.95
10^{-4}	136	1101	0.0163	0.7865	4000	0.0150	0.6395	8.67	14.70
10^{-5}	136	3621	0.1552	0.9283	4000	0.1552	0.9279	0.00	0.04
10^{-6}	136	11595	0.6425	0.9769	4000	0.6390	0.9631	0.35	1.38
10^{-7}	136	36811	0.9389	0.9926	4000	0.9200	0.9667	1.89	2.59
10^{-8}	136	116552	0.9904	0.9977	4000	0.9622	0.9671	2.82	3.06
10^{-9}	136	368714	0.9980	0.9993	4000	0.9666	0.9671	3.14	3.22
10^{-10}	136	1166123	0.9995	0.9998	4000	0.9671	0.9671	3.24	3.27
10^{-11}	136	3687750	0.9998	0.9999	4000	0.9671	0.9671	3.27	3.28
10^{-12}	136	11661965	1.0000	1.0000	4000	0.9671	0.9671	3.29	3.29

Adaptive MTU sizing can achieve a data throughput performance increase of 43% to 0.04% for SR-ARQ for bit error rates of 10^{-3} to 10^{-7}. As the bit error rate increases toward a maximum useable rate of 10^{-3}, adaptive MTU sizing provides larger and larger performance gains. For links operating in high bit error rate environments, adaptive MTU sizing provides a substantial data throughput improvement. Assuming that a typical link spends 50% of the time at 10^{-7}, 15% of the time at 10^{-6} and 10^{-8}, 7.5% of the time at 10^{-5} and 10^{-4}, and spends 5% of the time operating at a bit error rate of 10^{-3}, then adaptive MTU sizing yields a 5.2% increase in data throughput. A typical throughput improvement of 5.2% is therefore expected from the use of adaptive MTU sizing when used with SR-ARQ. Half of this improvement, or 2.6% gain, is expected when adaptive MTU sizing is used with Go-Back-N ARQ.

5.9.1.5 QoS Service Selection and Implementation Approach

QoS selection affects data throughout in that the more QoS functions that are in use, the more processing is required. The hardware implementation approach of using FPGAs in parallel is expected to improve SR-ARQ and all QoS function processing to a point where 100 Mbps can be processed even when the worst case QoS function combination is in use. No reduction in data throughput is expected from the use of QoS functionality, even when the highest processing and overhead bit transmission QoS functions are all selected at one time.

5.9.1.6 Upper Layer Protocol Removal/Encapsulation

When the processing of upper layer protocols (e.g., IP, UDP or TCP) is removed through the use of only ISLP QoS functionality, an additional 44% to 70% data throughout improvement is achieved from the reduced processing time and protocol overhead bit transmissions. Table 8 depicts upper layer protocol processing measurements made by MiTech on a typical computer system connected to a 100 Mbps link. Similar results were measured on a SUN Microsystems UltraSPARC workstation running the Solaris operating system.

Table 8. Upper Layer Protocol Removal/Encapsulation Performance Gains

UPPER LAYER PROTOCOL PROCESSING TIMES							
LINUX 2.0.27 Operating System on Pentium Pro 167 MHz PC with 3Com FastEtherlink BusMaster (3c595) Network Adapter on 100 Mbps FastEthernet							
Approx. Bit Error Rate (p_b)	Message Size	Message Arrival Interrupt Time	IP Protocol Start Time	Upper Layer Protocol Completion Time	IP and Upper Layer Protocol Processing Time	Total Processing Time	IP and Upper Layer Protocol Processing Time (% of Total Time)
Bits	Bytes	(μs)	(μs)	(μs)	(μs)	(μs)	(%)
10^{-7}	10	52100	53929	55818	1889	3718	51
10^{-7}	100	835285	837178	839169	1991	3884	51
10^{-7}	200	522122	524135	526190	2055	4068	51
10^{-7}	500	936124	938317	940325	2008	4201	48
10^{-7}	1000	628490	631059	633088	2029	4598	44
10^{-7}	1500	647266	647503	654236	3927	6970	56
10^{-7}	2000	272241	272478	279641	4357	7400	59
10^{-7}	4000	468194	468443	478937	7463	10743	70
10^{-7}	10000	585142	585380	607717	18347	22575	81
10^{-7}	65000	265938	266171	357004	95056	108290	88

A typical throughput improvement of 70% is expected from the removal (via non use or encapsulation) of upper layer protocol functionality in ISL transmissions.

5.9.1.7 Upper Layer Protocol Implementation

Table 9 depicts upper layer protocol processing measurements made by MiTech on a typical computer system connected to a 100 Mbps link.

Table 9. Upper Layer Protocol Implementation Performance Gains

UPPER LAYER PROTOCOL IMPLEMENTATION EFFECT ON LINK PERFORMANCE						
LINUX 2.0.27 Operating System on Pentium Pro 167 MHz PC with 3Com FastEtherlink BusMaster (3c595) Network Adapter on 100 Mbps FastEthernet						
Approx. Bit Error Rate (p_b)	Message Size	IP and Upper Layer Protocol Processing Time	IP and Upper Layer Protocol Processing Time	Application Level Link Data Throughput	Application Level Link Data Throughput	IP and Upper Layer Protocol Data Throughput Improvement
		LINUX	LINUX with INCA^{PatPend}	LINUX	LINUX with INCA^{PatPend}	LINUX with INCA^{PatPend}
Bits	Bytes	(μs)	(μs)	Mbps	Mbps	(%)
10^{-7}	10	1889	15	0.02	0.06	274
10^{-7}	100	1991	18	0.21	0.52	255
10^{-7}	200	2055	42	0.39	1.03	261
10^{-7}	500	2008	45	0.95	2.51	263
10^{-7}	1000	2029	79	1.74	4.78	275
10^{-7}	1500	3927	110	1.72	5.51	320
10^{-7}	2000	4357	160	2.16	7.18	332
10^{-7}	4000	7463	305	2.98	12.26	**411**

Upper layer protocol implementation greatly affects the overall data link throughput performance. This is true even though upper layer protocol performance is only loosely coupled to data link protocol operation. If upper layer protocols are going to be used over an ISL and if they are implemented in software, then optimization of upper layer protocols is a must for improved data throughput.

Using mainly memory access reducing techniques, MiTech has implemented the standard compliant IP, TCP and UDP upper layer protocols in a much more efficient manner. Table 9 depicts upper layer protocol processing measurements made by MiTech on a typical computer system connected to a 100 Mbps link. Similar results were measured on a SUN Microsystems UltraSPARC workstation running the Solaris operating system. As depicted in Table 9, MiTech's patent pending INCA upper layer protocol implementation of the IP, UDP and TCP protocol combinations improves data throughput by as much as 411%.

Assuming that a typical link spends 50% of the time at 10^{-7}, 25% of the time at 10^{-6}, 7.5% of the time at 10^{-5} and 10^{-4}, and spends 10% of the time operating at a bit error rate of 10^{-3}, then a typical throughput improvement of 354% is expected from the improved implementation (e.g., MiTech's INCA[PatPend]) of upper layer protocols in point-to-point link transmission. The performance improvement from a more efficient upper layer protocol implementation is typically greater than that from all the other data link protocol QoS performance optimizations combined.

5.9.2 DLP PERFORMANCE SUMMARY

Compression, SR-ARQ, adaptive FEC, adaptive MTU and either not using an upper layer protocol or optimization of upper layer protocol implementation define the pure performance modifications and additions of the proposed ISLP. Other QoS additions might provide performance improvements under certain circumstances, e.g., the elimination of the equivalent QoS functions in upper layer protocols or in the end user application, and the adaptation of FEC and other ISLP processing in accordance with knowledge about the user data. Table 10 summarizes the performance gains findings.

Table 10. Expected and Possible Performance Gains

PERFORMANCE IMPROVEMENT SUMMARY			
QoS Function or Mechanism	**Improvement (%)**		
	Best	**Worst**	**Expected**
Compression	1000	2	50
Multiple Buffer SR-ARQ	100	2	31
Adaptive FEC	50	7	7
Adaptive MTU	14.7	0	5.2
QoS Service Selection and Implementation	- -	- -	0
Data Link Protocol Performance Increase	**1165**	**11**	**93**
Upper Layer Protocol Removal/Encapsulation	70	51	70
Data Link Performance Increase -	**1235**	**62**	**163**
Upper Layer Protocol Implementation	411	255	354
TOTAL POSSIBLE PERFORMANCE INCREASE	**1646**	**317**	**517**

5.9.3 ISLP vs. CCSDS, SCPS IP/TCP, and Internet IP/TCP

In the previous section, the performance of a link using the ISLP was evaluated relative to the performance of a link using an HDLC type of data link layer protocol. The performance of the new ISLP can also be measured relative to other existing satellite link implementations that employ more than a data link layer protocol, such as TCP/IP protocols running over the top of a data link layer protocol. Three common satellite link implementations are chosen for comparison to a new ISLP satellite link implementation:

1. CCSDS - Consultative Committee for Space Data Systems protocol stack
2. SCPS TCP - Space Communications Protocol Specification Transport Control Protocol
3. Internet TCP - the standard Internet protocol suite Transport Control Protocol.

5.9.3.1 CCSDS Space Link Protocols

The CCSDS was formed in 1982 by the major space agencies of the world to provide a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of ten member agencies, twenty-three observer agencies, and over 100 industrial associates. Since its establishment, it has been actively developing recommendations for data and information systems standards to a) reduce the cost to the various agencies of performing common data functions by eliminating unjustified project- unique design and development, and b) promote interoperability and cross support among cooperating space agencies to reduce operations costs by sharing facilities. CCSDS products are data and information system Recommendations (Blue Books). These Recommendations serve as baseline documents for the applicable standards of the participating agencies. It is an iterative process, first among technical panel experts and then among the CCSDS agencies. Final approval is by consensus of the voting members. CCSDS Recommendations are also being converted into ISO International Standards. CCSDS Recommendations are routinely submitted to the ISO through ISO Technical Committee 20 (TC 20 Aircraft and space vehicles)/ Subcommittee 13 (SC 13 Space data and information transfer systems). Many CCSDS Recommendations have already been adopted as international standards, and many others are currently in the review process leading to adoption by ISO. The goal of CCSDS is to establish a world wide, open, CCSDS compatible virtual space data system for international cross support, interoperability, and science information interchange. The CCSDS protocol stack includes a physical layer, data link layer and an application layer (or user specified upper layer protocol).

5.9.3.2 SCPS Space Link Protocols

In the fall of 1992, NASA and the Department of Defense jointly established a technical team (the SCPS Technical Working Group, or SCPS-TWG) to explore possibilities for developing common space data communications standards. By the end of 1993, the team concluded that wide segments of the U.S. civil and military space communities have common needs for protocols to support in-flight monitoring and control of civil and military spacecraft. The most widely used protocols today are the Internet protocols. These are usually referred to as TCP/IP, but, in fact, comprise more than fifty Internet standards. This communications baseline is robust and flexible, as a result of hundreds of thousands of engineering hours and years of use and testing. The SCPS provide modifications and extensions to only a few of these Internet protocols, in order to meet the special requirements of space communication. A primary goal of the SCPS effort was to extend Internet connectivity into space. The rationale for this approach is that both the data systems and the personnel (designers, operators, users) associated with space missions are already using Internet protocols. The communications services that they need in space are very similar to those they have in ground networks. The easiest, lowest risk, and most direct way to achieve this goal was to deemed to be to adapt the protocols that are used on the ground. To provide reliable end-to-end SCPS Transport Protocol (SCPS-TP) services, the Internet TCP and UDP were adapted to meet unique space mission requirements, using IETF defined extensions and SCPS defined modifications. The SCPS protocol layers are specified in a set of four CCSDS Recommendations [CCSDS1-4]. The SCPS protocols support the transfer of space mission data through space-to-ground and space-to-space data subnetworks. These protocols are not intended for transfer of space mission data that occurs wholly within ground systems, but rather are focused on the unique requirements of data transfer through subnetworks that involve a space data transmission path. The SCPS can be used as an integrated protocol stack, or the individual protocols can be used in combination with CCSDS or Internet protocols to create custom profiles to support the requirements of particular missions. Previous CCSDS protocols were not designed to provide the functionality that the SCPS offer. CCSDS protocols used for return (or downlink) data provide error-protected, sequenced data streams. This service supports real-time data acquisition and quick look analysis. It also makes possible the production of best-effort (nearly complete) data sets from multiple dumps of data. But these

protocols were not intended to support automatic, real-time retransmission to provide complete or best-effort data streams, or to provide reliable file transfer. Adding these services would require additional protocol layers and complexity equal to the SCPS approach, but would not yield the benefit of Internet compatibility, nor capitalize on the vast experience with Internet protocol development and use. The SCPS protocols include:

1. A file handling protocol (the SCPS File Protocol, or SCPS-FP), optimized towards the up-loading of spacecraft commands and software, and the downloading of collections of telemetry data
2. An underlying retransmission control protocol (SCPS-TP), optimized to provide reliable end-to-end delivery of spacecraft command and telemetry messages between computers that are communicating over a network containing one or more potentially unreliable space data transmission paths
3. A data protection mechanism (the SCPS Security Protocol, or SCPS-SP) that provides the end-to-end security and integrity of such message exchange
4. A scaleable networking protocol (the SCPS Network Protocol, or SCPS-NP) that supports both connectionless and connection-oriented routing of these messages through networks containing space data links.

Some form of data link protocol is required in order to run SCPS TCP or other protocols over a link.

5.9.3.3 Internet Link Protocols

The Internet technology that has resulted from research funded by the Advanced Research Projects Agency (ARPA)[1] includes a set of network standards that specify the details of how computers communicate, as well as a set of conventions for interconnecting networks and routing traffic. Officially named the TCP/IP Internet Protocol Suite and commonly referred to as TCP/IP (after the names of its two main standards), it can be used to communicate across any set of interconnected networks. Although the TCP/IP technology is noteworthy by itself, it is especially interesting because its viability has been demonstrated on a large scale. It forms the base technology for a global Internet that connects homes, university campuses and other schools, corporations, and government labs in 61 countries. An outstanding success, the Internet demonstrates the viability of the TCP/IP technology and shows how it can accommodate a wide variety of underlying network technologies. The Internet protocols include more than 50 protocols from the data link, network, transport, session, presentation and application protocol layers. The protocols of interest are the Internet network protocol - IP, and the transport protocol - TCP. Some form of data link protocol is required in order to run TCP/IP protocols over a link.

5.9.4 ISLP vs. CCSDS, SCPS IP/TCP, and Internet IP/TCP Performance Summary

The CCSDS and ISLP protocol can be used by themselves for a complete ISL transmission capability. The SCPS and Internet protocols require lower network and data link layer protocols in order to form a complete link transmission capability. Table 11 depicts the performance of various link protocol combinations that form a complete ISL transmission capability. Figures 24 and 25 illustrate the ISLP satellite link performance versus SCPS and Internet satellite link protocol combinations. As can be seen from Table 11, and Figures 24 and 25, the new ISLP provides a substantial performance improvement over existing satellite link implementations despite offering the QoS functions which the other link implementations do not offer. The ISLP is the only implementation providing a useable link at high error rates. SCPS is optimized for ground to satellite link transmissions and requires upper layer protocols and falls short of ISLP performance, particularly, as link bit error rates increase. Internet TCP/IP is obviously not suited for satellite link transmission due to its design and operation based on terrestrial link delay and error characteristics. CCSDS suffers from a high overhead due to its design as a general purpose, multiple user, multi-addressable spacecraft experiment/entity protocol. The best existing link offering, SCPS, optimized for satellite link transmission, falls 7% short of the ISLP (non compression) link utilization. If the ISLP

[1] ARPA was called the Defense Advanced Research Projects Agency for several years during the 1980s

compression QoS is utilized, ISLP would outperform the next best satellite link implementation (SCPS) by more than 50%.

Table 11. Complete Satellite Link Transmission Capability Performance Comparison

SATELLITE LINK UTILIZATION PERFORMANCE COMPARISON						
Complete Link Transmission	Link Bit Error Rate					
Capability Protocol Stack	1E-08	1E-07	1E-06	1E-05	1E-04	1E-03
SCPS [CCSDS5, CCSDS6] SCPS TCP-only	94	94	91	85	61	0
SCPS TCP/IP over ISLP	93	92	88	78	47	0
SCPS TCP/IP over HDLC	92	89	69	22	2	0
SCPS TCP/IP over CCSDS	55	54	51	43	22	0
Internet [CCSDS5] Internet TCP-only	91	76	53	39	13	0
Internet TCP/IP over ISLP	90	74	51	35	9	0
Internet TCP/IP over HDLC	90	72	40	10	0	0
Internet TCP/IP over CCSDS	53	44	30	20	5	0
CCSDS [1]	59	58	57	52	38	0
HDLC (Go-Back-N) [2]	99	96	77	26	3	0
ISLP [2]	100	99	98	93	79	44

[1] CCSDS data estimated from [CCSDS5,CCSDS6]

[2] From Table 5

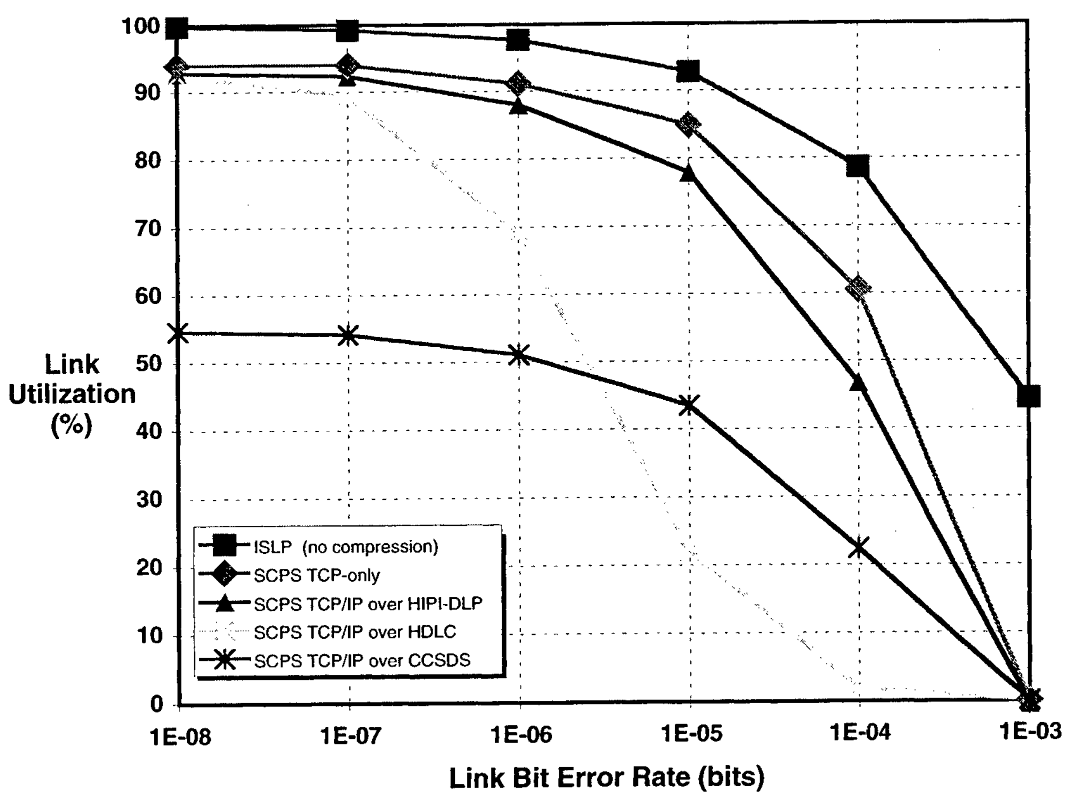

Figure 24. ISLP Link Performance Versus SCPS Link Protocol Combinations

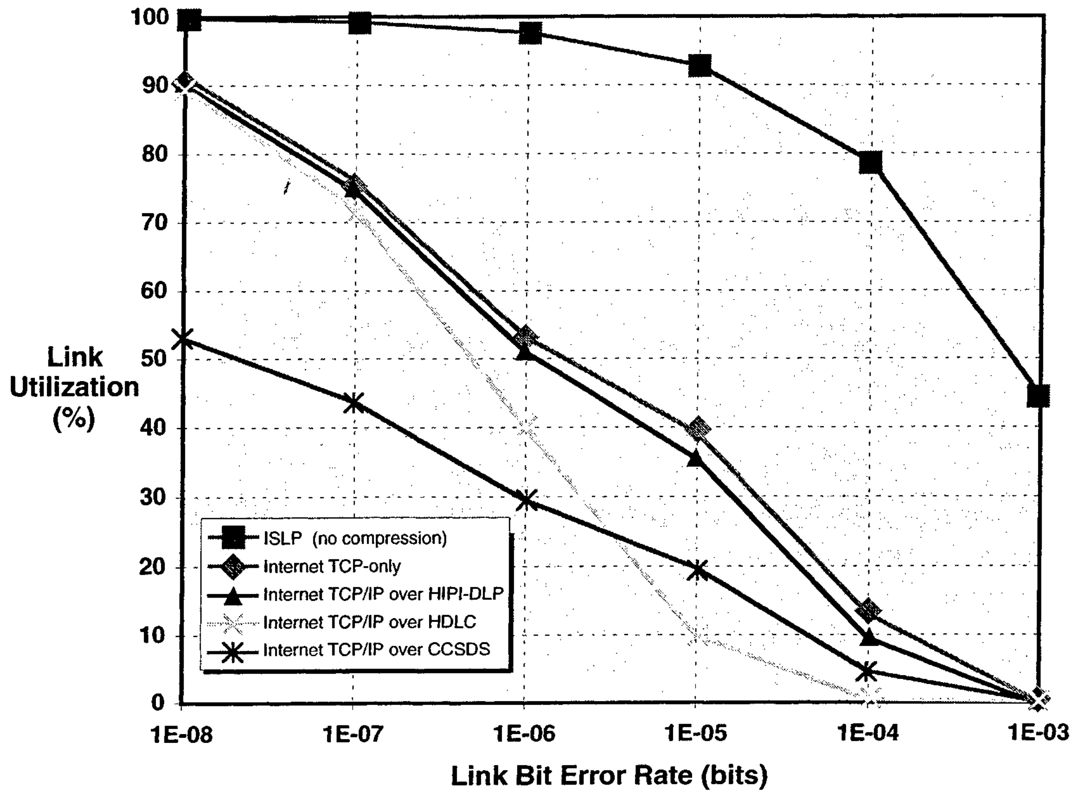

Figure 25. ISLP Link Performance Versus Internet Link Protocol Combinations

In the cases where the new ISLP is utilized with the TCP/IP protocols (SCPS or Internet), where TCP/IP functionality is used to control link transmissions, ISLP still provides performance improvement, especially in high link bit error rate situations. In cases where the TCP/IP protocols are encapsulated within the ISLP data field of the ISLP messages, preserving TCP/IP functionality between end-to-end TCP/IP users on the ground, but not using TCP/IP functionality for satellite link control, ISLP can provide near the performance improvement of utilizing ISLP by itself, more than 50% with compression.

Encapsulation of TCP/IP protocols within the ISLP protocol data fields, would seem to be the best mode of operation for performance and maintaining end-to-end TCP/IP Internet interoperability. The utilization of the new ISLP in this manner can provide an approximately 70% increase in data throughput while providing a complete set of QoS functions and maintaining Internet interoperability.

5.10 Discussion

The added functionality and performance of the modified HDLC protocol may not required, particularly if no payload data and low data rates are transferred across the ISL. In this case, the recommendation is to use standard HDLC as the ISL data link layer protocol (ISLP). The use of the HDLC protocol provides the necessary link operation, data formatting and error handling functionality while maximizing the potential use of COTS wireless CDMA communications components such as FPGAs, firmware and existing hardware. The use of the existing, national or international standard protocol frame structures and bit definitions provides interoperability with existing satellite and terrestrial communication links including SCPS, CCSDS and the Internet protocol suites of TCP/UDP/IP. Links before and after the satellite link using the ISLP (HDLC) require no modifications or new information exchange interfaces.

An Application Program Interface (API) will provide the minimum functionality needed to initiate, terminate, suspend, test and otherwise operate the ISL. The API provides the interface to

the ISL functionality for the external ISL subsystem applications that require access to ISL functionality or link data transmissions.

Modification of the HDLC protocol for reduced overhead and improved performance is possible while still being able to utilize COTS components. A detailed description of this process and its implementation has been provided. A flexible and widely applicable protocol enhancing mechanism is described that when applied to link protocols (data link - e.g., HDLC, network - e.g., IP or transport - e.g., TCP, UDP), enhances performance and functionality significantly over existing satellite link protocols. The protocol mechanism uses undefined, optional bit patterns in protocol headers and bits in the beginning of the user data field in existing standard link protocols to define new performance and QoS functions. The added protocol QoS functions, including compression and multiple buffer SR-ARQ, increase user data throughput and provide the differentiated data transmission services requested by network link providers and users. The mechanism was applied to an existing data link protocol, HDLC, in order to meet the SBIR objective of defining a higher performance data link protocol. The new protocol functions and resulting higher performance are implemented transparent to the user, the existing communication protocols and link equipment.

A recommended path for the ISL protocol evolution to higher and higher data rates is to begin with standard HDLC for the low data rate flight experiment. When higher data rates are required for later satellite missions (e.g., radar payload data across the ISL), using compression on the data before ISL HDLC encapsulation and transmission of the data provides an excellent performance to cost, risk and complexity tradeoff. Once data rates come into the 100 Mbps range and ISL distances and link parameters begin to increase and vary over larger ranges, the reexamination and potential use of the described modified HDLC protocol as the ISLP is encouraged.

6. ISL EDU DEFINITION

An ISL EDU is a prototype ISL implementation that allows for the validation and testing of the proposed architecture and components in the controlled environment of a testbed.

6.1 Purpose

The purpose of the ISL EDU definition is to provide an ISL demonstration system that meets the TS21 flight experiment requirements and program schedule. An ISL EDU is defined that demonstrates the feasibility of achieving the three main technology requirements: payload data transmission, ranging and timing calculations.

6.2 Scope

The scope of the ISL EDU definition is limited to what can be achieved by an October 2000 time frame within the budget constraints of the SBIR and TS21 funding vehicles. The ISL EDU will demonstrate the ability to transmit data via wireless DS-CDMA as well as demonstrate the ability to perform ranging and timing synchronization functions. Demonstration of the three main technology requirements: data transmission, ranging and timing calculations, will be provided on a proof of concept level and not to the final operational specifications. The ISL demonstration unit will be limited to providing the necessary functionality for assuring that the operational ISL system requirements can be met through extrapolation of current architectures, components and implementation approaches.

6.3 Approach

Maximum use of COTS components is made with the ISL unique requirements confined to a minimum of FPGA and software components. Cost and schedule are traded off against ISL capabilities in an effort to demonstrate the most ISL functionality for the short development time and amount of funds available.

6.4 EDU Description

Two possible demonstration systems are presented with varying costs and ISL functionality demonstration capabilities. Figures 26 and 27 depict the proposed ISL EDU possibilities.

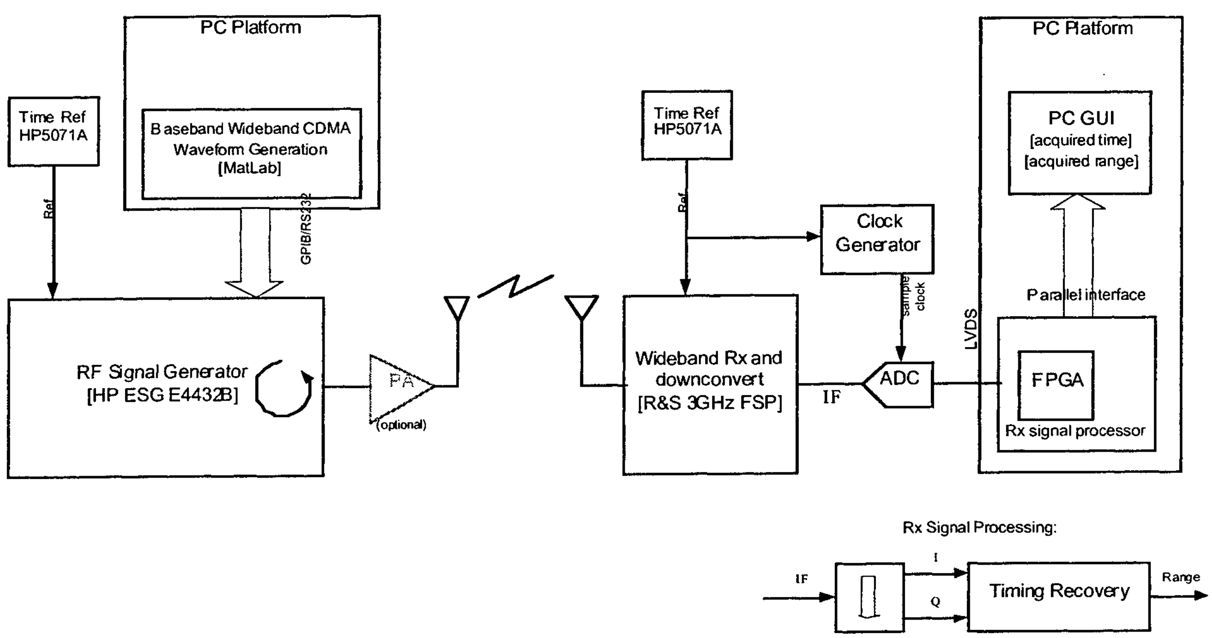

Figure 26. TS21 ISL Demonstration System

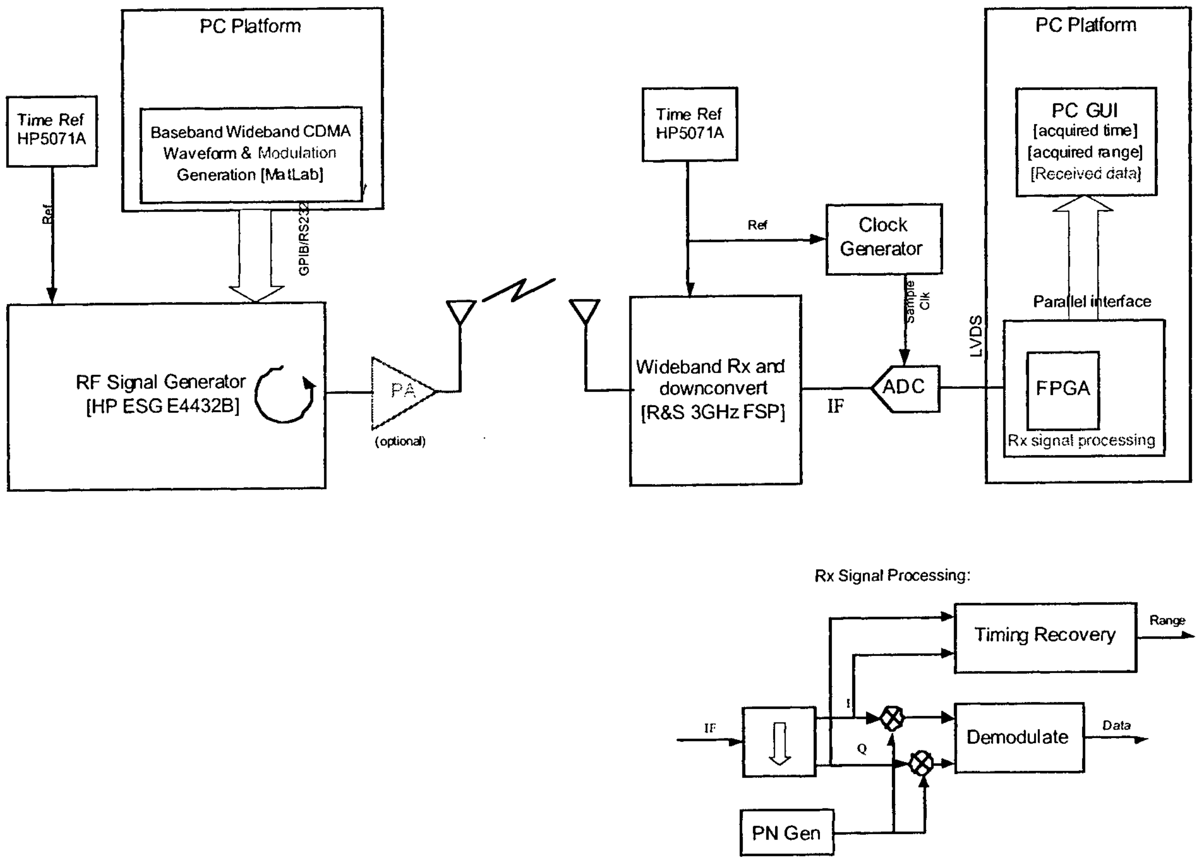

Figure 27. TS21 ISL Enhanced Demonstration

The ISL demonstration system in Figure 26 is possibly to be the fastest route to achieve a system that can measure distance between TX and RX utilizing DS-CDMA modulation techniques. COTS system components for DS-CDMA are not in abundance and those that are available do not provide the demodulation signals that are required for calculating time offset (and hence range). They are also unlikely to be suitable for the performance enhancements required beyond October 2000. Test equipment provides the flexibility that may be required for the present and future investigations that are required for this project. The digital backend receiver is essential to provide the DS-CDMA demodulation functions required for range determination and for future development. Data is not supported by this system as it was thought not to be a significant technological challenge (more a matter of development time) compared to the timing and ranging capabilities.

The transmission waveform is a fixed DS-CDMA sequence that is pre-loaded into the Hewlett-Packard (HP) Electronic Signal Generator's (ESG) arbitrary waveform generator. The HP ESG is also a vector signal generator and as such is able to up-convert the baseband waveform to RF. A Power Amplifier (PA) may be required to boost the transmit signal to achieve the required distance for the demonstration.

At the receive end, the Rohde & Schwarz (R&S) frequency spectrum processor (FSP) is used to downconvert the RF signal to an IF of 20.4 MHz. This is sampled by an A/D converter (ADC) module and passed via a high-speed digital (low-voltage differential signaling - LVDS) interconnect to the baseband processor. The primary processing element of the baseband processor is a Xilinx Virtex FPGA. The Virtex device supports the algorithms required to extract the received signal's time-offset from the reference signal. This measurement is passed to the host PC that performs the range calculation for display.

The time references are off-the-shelf components from HP. The two time reference units can be synchronized via a physical interconnect and their relative drift is then defined by the

specifications. Each time reference will provide the signals for frequency locking of the local system (a 10 MHz reference) and the 1 Hz signal for repetitive triggering of the transmission of the waveform stored in the HP ESG. In the receiver, the time offset between the 1 Hz trigger and the received synchronization pattern in the CDMA waveform will provide the data for the range estimation.

The equipment configuration of Figure 26 will support a DS-CDMA on-air bandwidth of around 8 MHz. This is expected to be sufficient to meet the range and information rate requirements of the October 2000 demonstration. It is worth noting that ranging accuracy will, in part, be a function of the bandwidth of the DS-CDMA system.

Figure 27 illustrates the demonstration system enhanced with a data transmission facility. The elements marked in red (beware if this document has been printed) highlight the additions/changes to the demonstration system from Figure 26.

The fixed length DS-CDMA sequence that is stored in the HP ESG can be modulated with data up to a maximum length (to be determined). For example, a Matlab program would allow a text string to be entered via a graphical user interface (GUI) and then would generate the modulated DS-CDMA data sequence for download to the HP ESG. This is a non-real-time operation. The ESG would then repeatedly transmit the modulated signal which is then received and demodulated in order to extract the data string. The string and the range estimation would be displayed on the PC screen. The rate of the data transmission would likely be in the range 200 kbps to 500 kbps using a modulation format that has yet to be determined.

The primary additional functional elements of the demonstration system in Figure 27 are: string input and DS-CDMA modulation via Matlab, demodulation functionality in the baseband processor and received data display functionality at the receiver.

7. CONCLUSIONS

It seems possible to be able to implement an ISL system which transmits 100 Mbps, receives multiple 100 Mbps data transmissions, calculates satellite relative (to another satellite's ISL transmitter) position to 3 mm and determines inter-satellite cluster timing synchronization to 20 ps. Using DS-CDMA technology and components, an ISL system operating over ranges of a few meters to 5000 km should be achievable in a 20 W, 5 kg, 0.3 m^3 package at a cost of $300K in quantities of $\geq$ 300. The use of FPGAs, high speed D/A, A/D converters allows for the implementation of a wireless RF DS-CDMA communications system with HDLC data link protocol interoperability. The entire ISL system can be almost completely implemented in the digital domain, providing exceptional performance and functionality in a small and cost effective package.

8. RECOMMENDATIONS

Inter-satellite link operation for the distributed, space based SAR mission includes operations deemed technologically stressing and encompassing a wide range of ISL operational profiles. Extremely high data rates, spacecraft subsystem support, stressing volume, weight, power and time delay/processing restrictions, etc., should make the ISL Operations Concept a useful ISL requirements source for a number of satellite missions.

The ISL requirements document defines and documents a set of ISL requirements for evaluating wireless communication technologies and defining recommended ISL implementations capable of conducting satellite missions. Additional uses for the requirements document include evaluating proposed ISL implementations, performing cost and risk tradeoffs and gaining user community acceptance of ISL implementations. Maintenance of the ISL Operations Concept and Requirements documents through periodic review and modification of content for updated ISL knowledge would extend the purposes and utility of these documents to a number of other satellite cluster, satellite LAN or virtual satellite type missions. The unclassified nature and conceptual information level should aid in ISL information dissemination.

With a high, preferably 20 to 100 Mbps data transmission capability, the ISL could provide additional satellite functions as well as having the support and backing of the immense commercial wireless communications community. For example, if each satellite in a cluster or virtual satellite LAN has to downlink payload data at a high rate (e.g., 100 Mbps), there is a high probability that no ground station can accommodate multiple simultaneous 100 Mbps links during one pass over the ground station. This would mean that multiple ground station passes would be required to downlink one experiment's worth of data. Multiple ground passes require difficult ground station scheduling and satellite orbit coordination with the possibility of orbit maneuvers required to provide the necessary data downlinking. With a high data rate ISL, downlinking of the payload data during the flight experiment could be performed with one pass over the ground station rather than via multiple passes. All payload data can be transmitted to one satellite in order to be downlinked from one satellite, greatly simplifying ground station scheduling and cluster management.

Without a high data rate ISL, real time processing of payload data in satellite clusters by the satellites in space is unachievable. Satellite LANs with low data rate LAN connections (i.e., ISLs) suffer the same drawbacks as terrestrial LANs with low speed connections. As witnessed to by the move from dial-up slow speed modem connections to cable modems and Digital Subscriber Loop (DSL) connections, high speed network link connectivity opens up new possibilities and markets.

Without a greater than 2 Mbps data transmission capability, an ISL has no commercial application and hence is of no interest to third party, commercial product funding parties. Without commercial appeal, an ISL is likely to suffer from a lack of industry support, with the manifestations of a lack of support including high initial and recurring costs. Commercialization is a prime requirement for SBIR funding. If SBIR funding is to continue to be available for ISL development, it is highly recommended that a greater than 2 Mbps data transmission capability remain an ISL requirement.

Because of the feasibility of an ISL as defined in this effort, the development of a CDMA based, high speed ISL is highly recommended to meet the needs of future space missions and to reap the benefits the support of the commercial wireless communications markets.

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